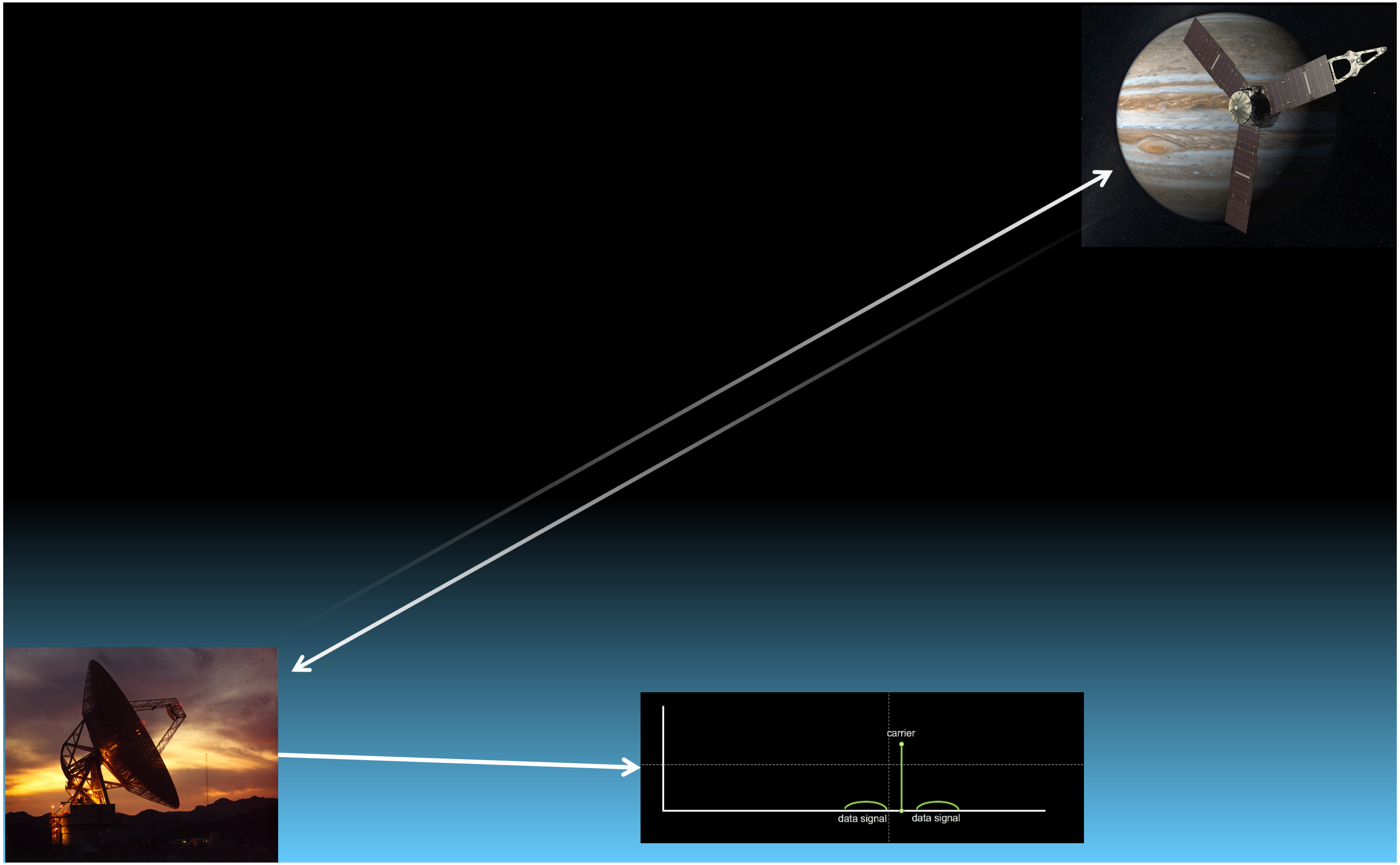
Radio Astronomy

Sardinia Deep Space Antenna Seminar Series

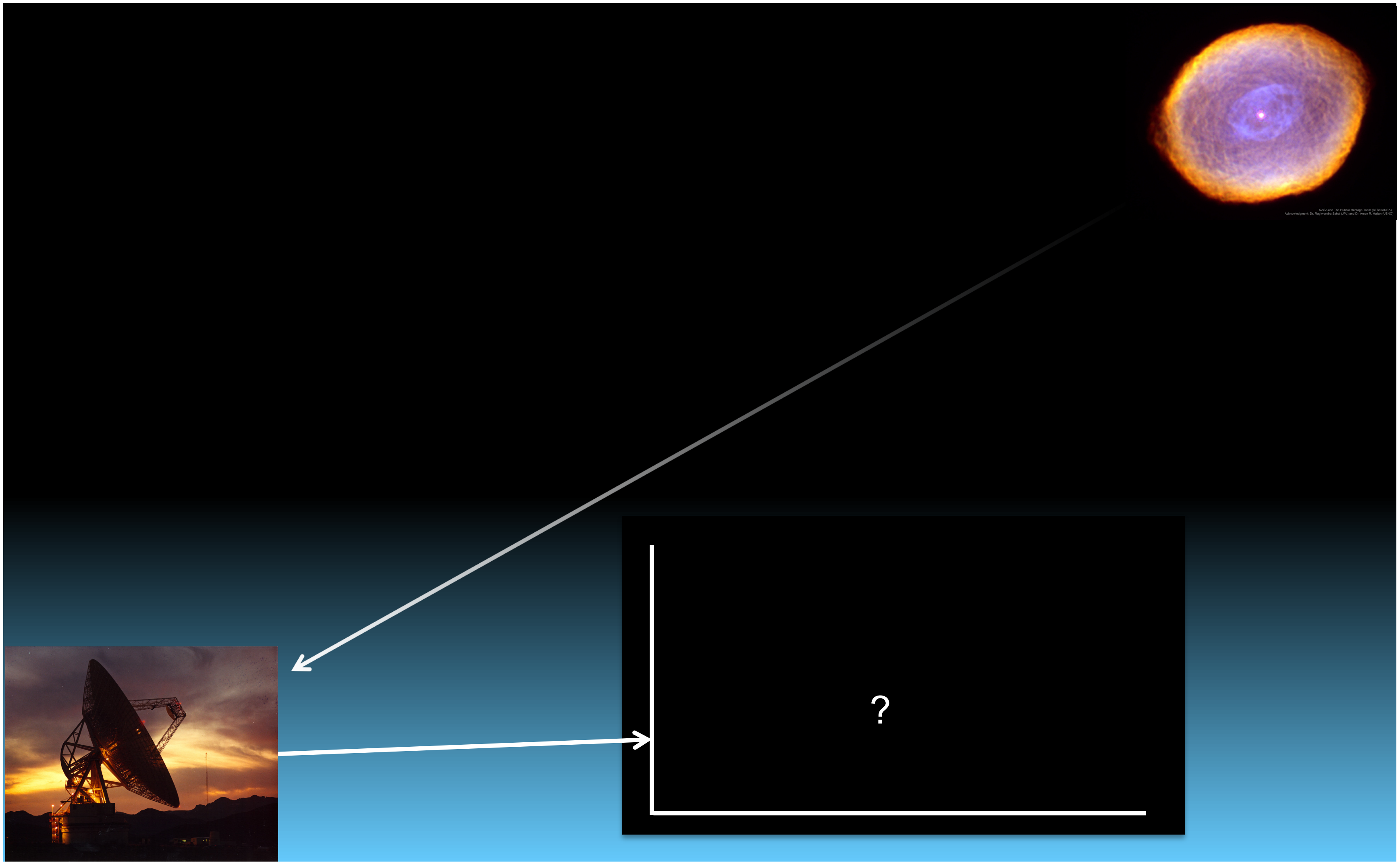
Joseph Lazio

Jet Propulsion Laboratory
California Institute of Technology

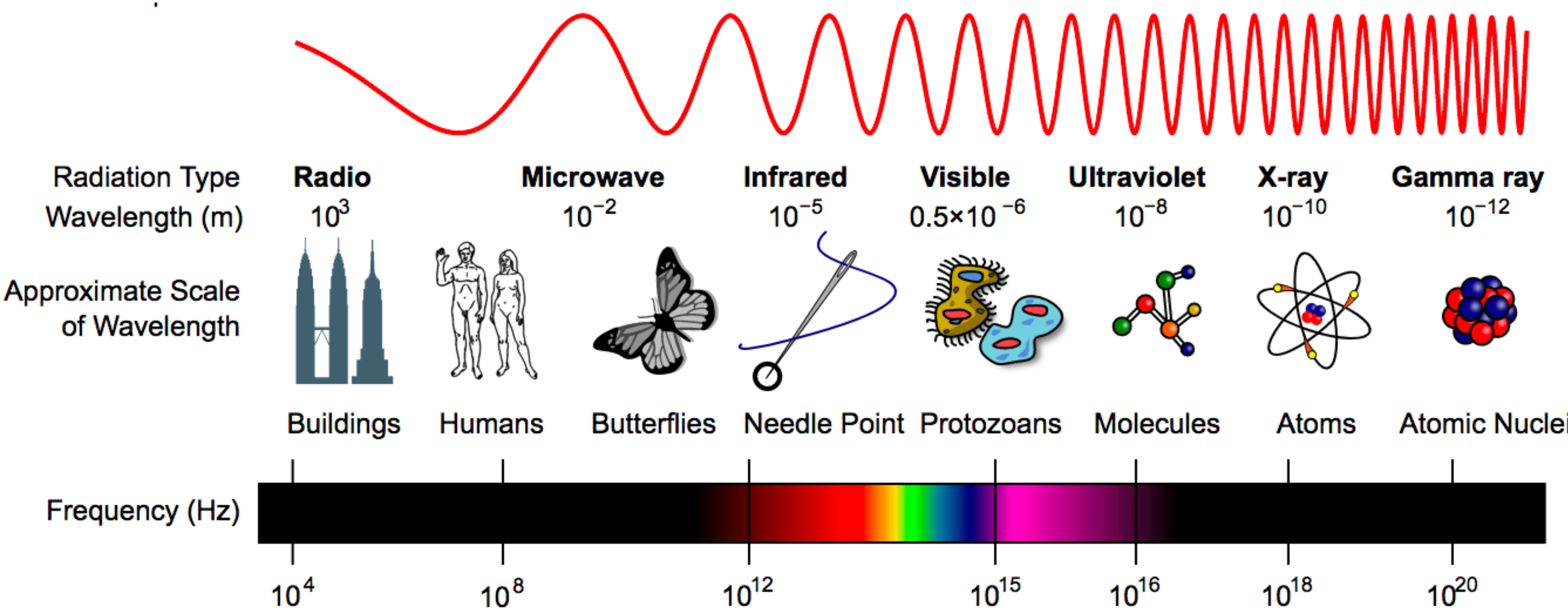
Spacecraft Telemetry, Tracking, & Command



Radio Astronomy



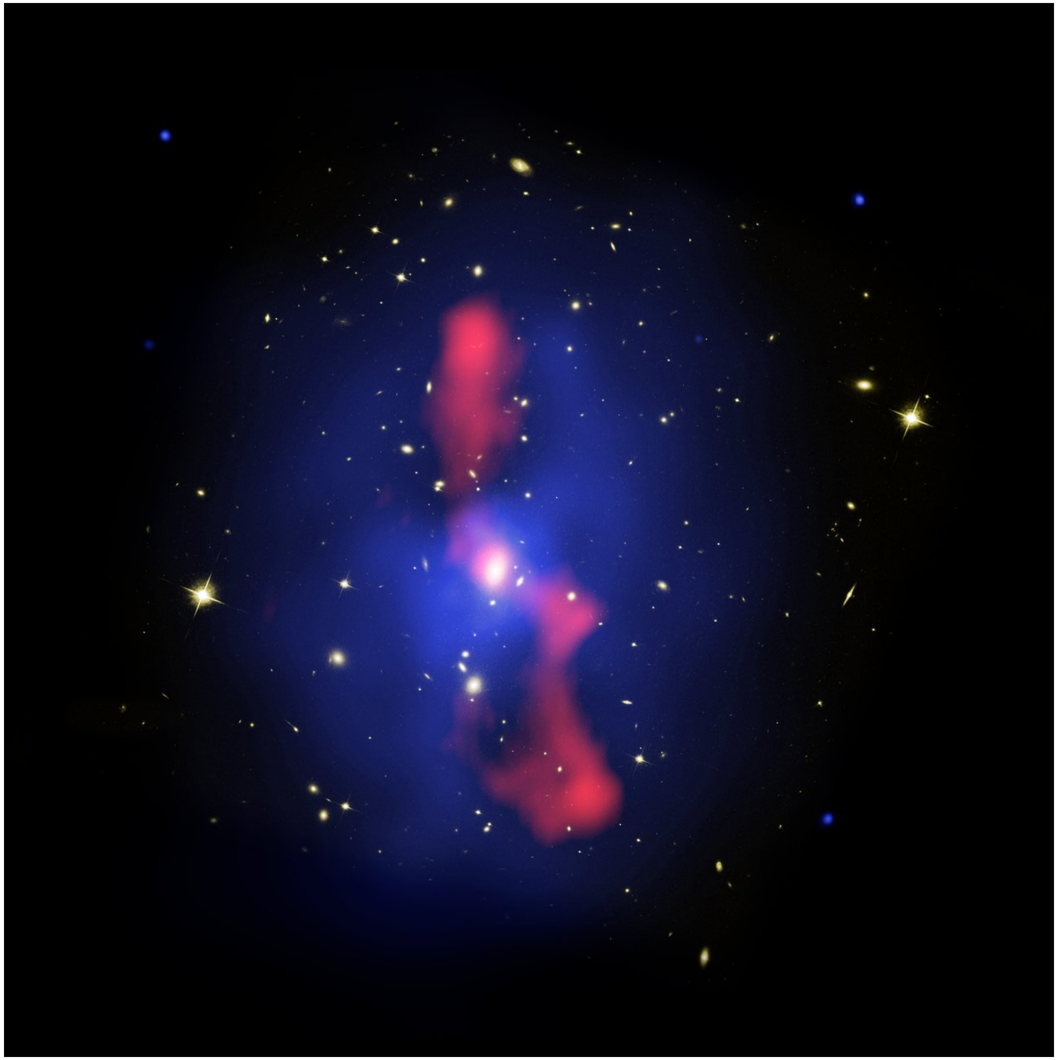
Electromagnetic Spectrum



Credit:
Wikipedia Images

Need Complete View of the Universe

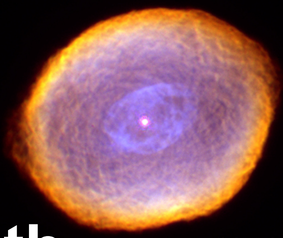
Electromagnetic Spectrum



MS 0735.6+7421

- **Cluster of galaxies**
  - **About 2.6 billion light-years away**
  - **In the constellation Camelopardalis**
- **Three views**
  - **Blue: Chandra X-ray Observatory**
  - **White: *Hubble Space Telescope***
  - **Red: Very Large Array**

Radio Astronomy



Large radio antennas, equipped with sensitive (cryogenic) microwave receivers

- **Spectroscopy**
  - **Complements ALMA, complements NASA and ESA far-infrared—sub-millimeter missions (e.g., Planck, *Herschel*, SOFIA)**
- **Very Long Baseline Interferometry (VLBI)**
  - **Complements VLBA, EVN, LBA; many NASA and ESA mission complements**
- **Time Domain**
  - **Many NASA and ESA mission complements**

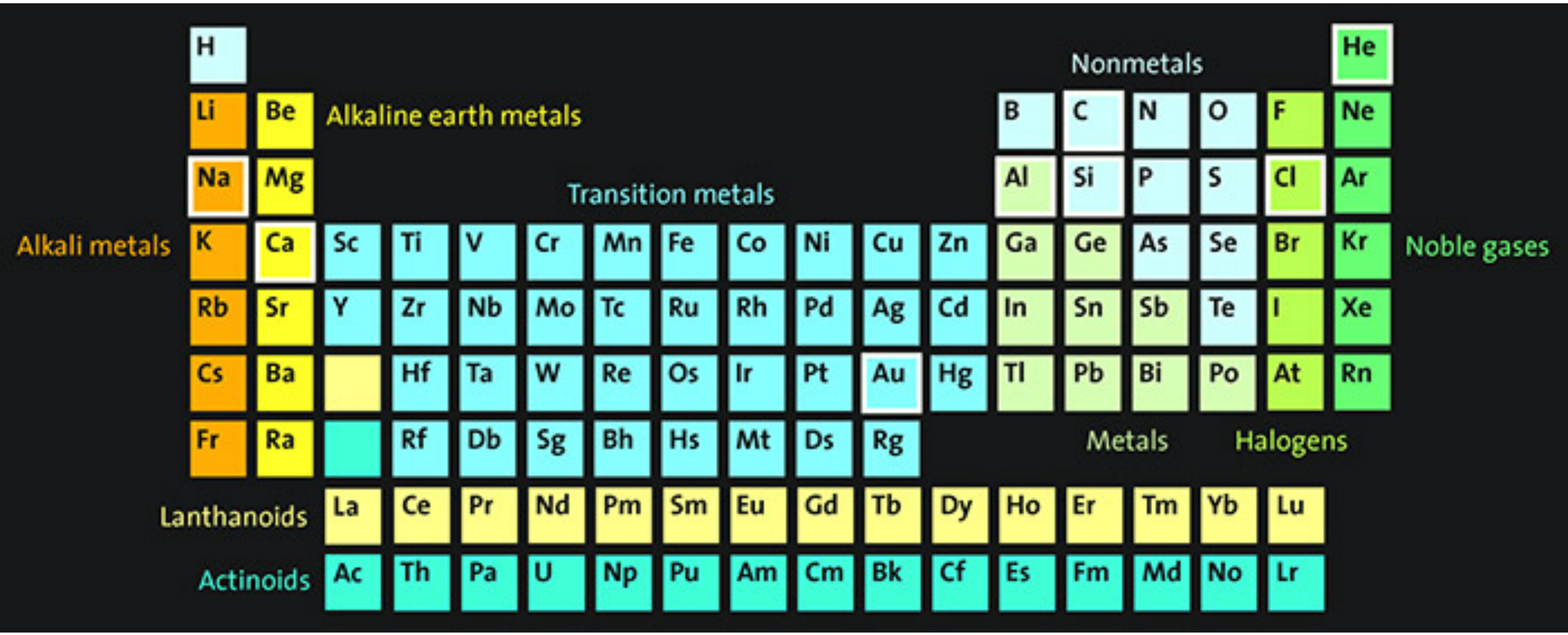
Radio Astronomy

Analysis of 69 Green Bank Telescope (GBT) publications (2017)

- **Spectroscopy: 38**
- **Time Domain: 21**
- **Very Long Baseline Interferometry (VLBI): 3**
- **Radar, Solar System: 3**
- **Instrumentation: 5**
- **Continuum/Theory/Other: 3**

Periodic Table

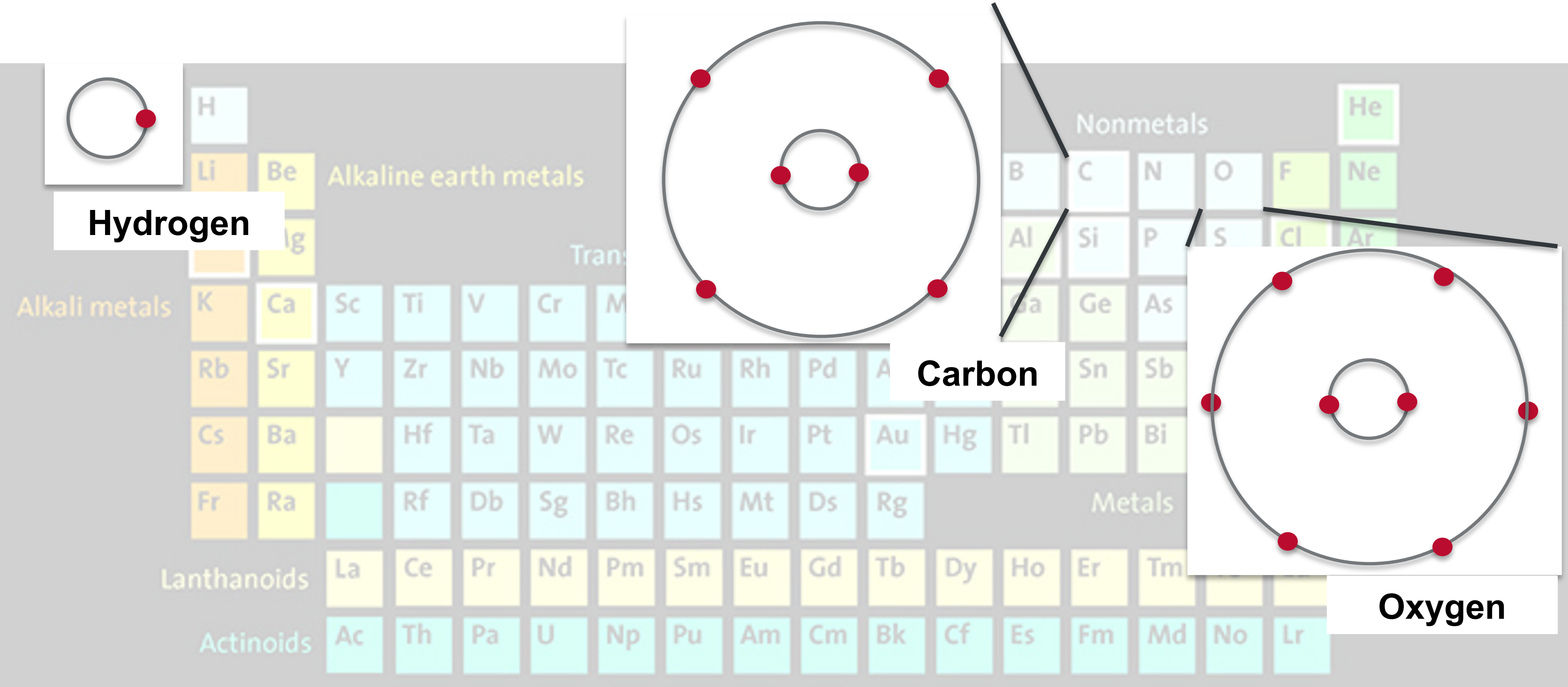
150 Year Anniversary!



Credit: Griffith Observatory

Periodic Table

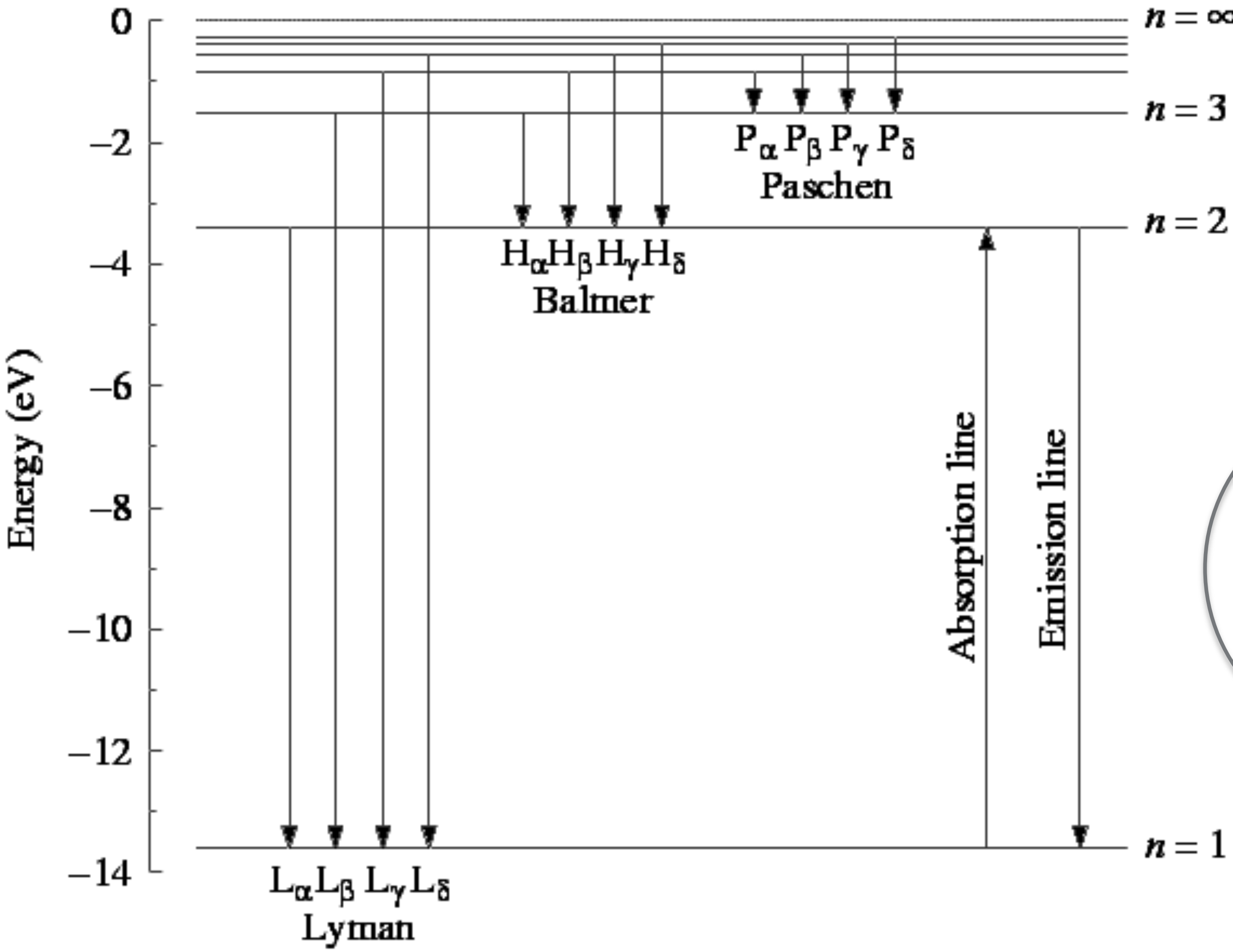
Chemical Elements

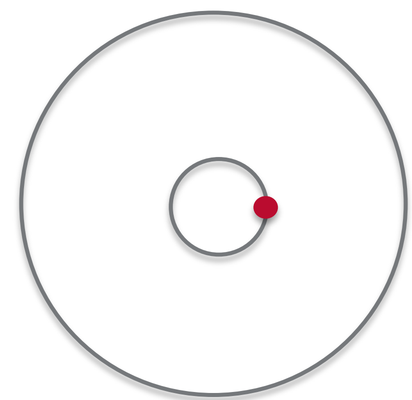


Credit: Griffith Observatory

Atoms and Quantitized Energy Levels

Hydrogen Energy Levels and Transitions

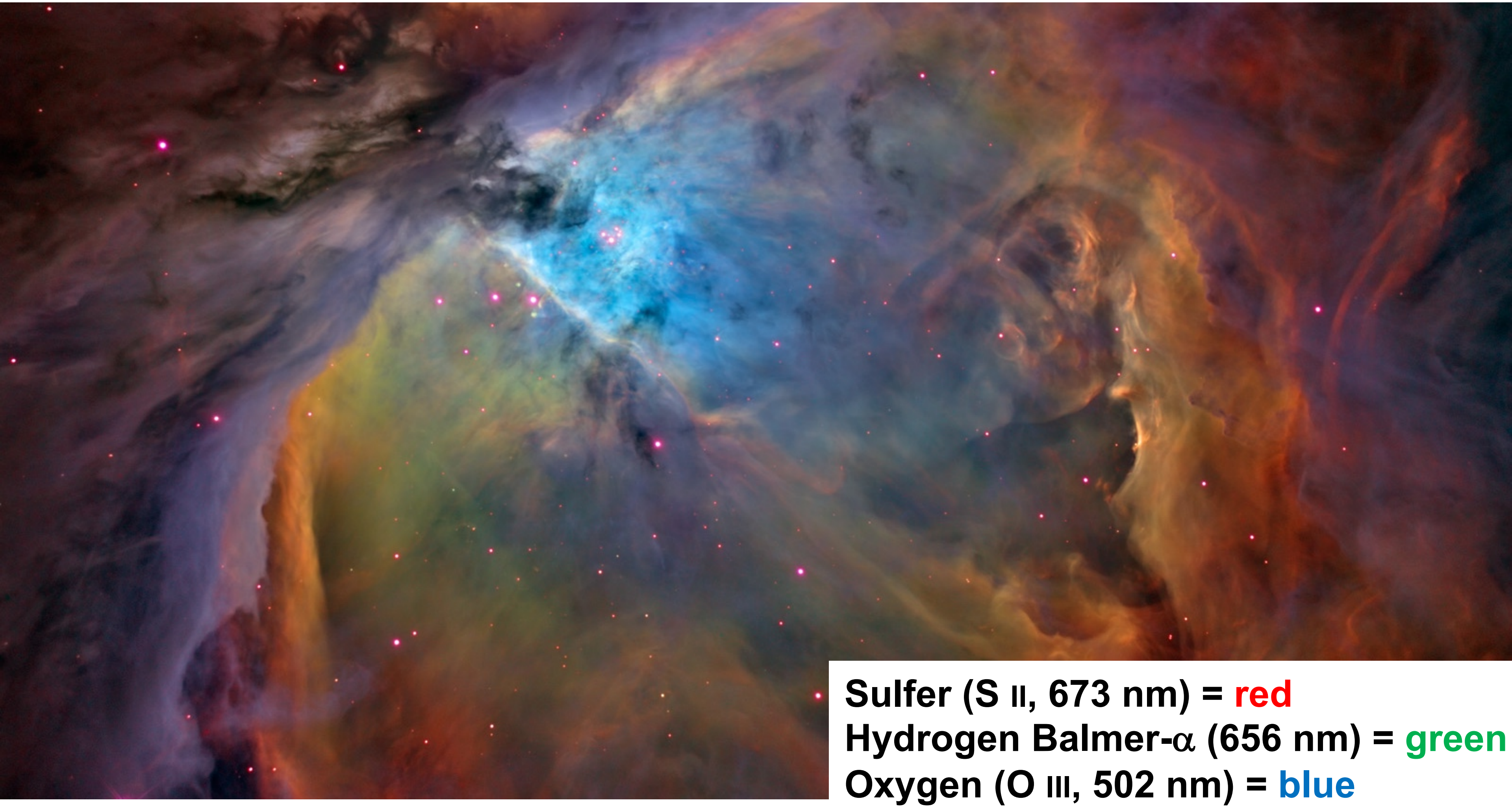




Credit: C. Mihos

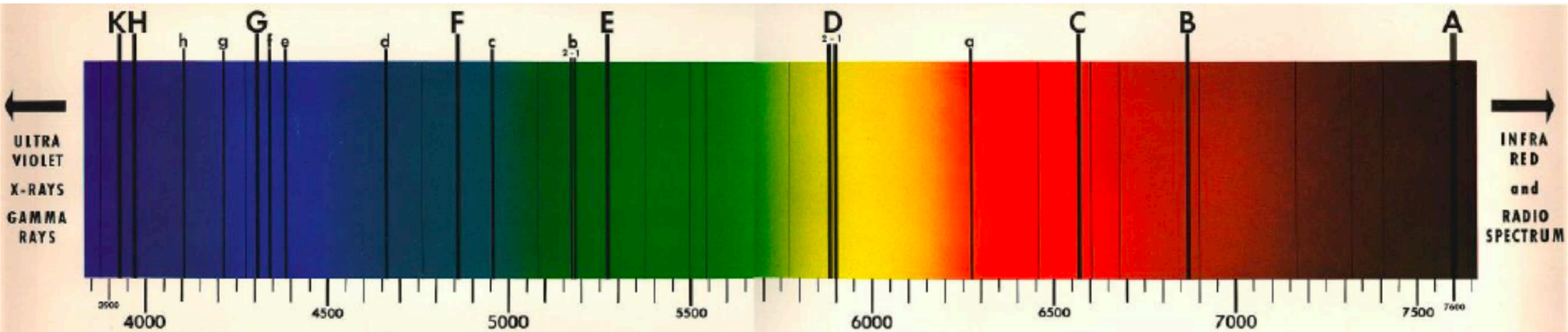
Spectral Lines

Orion Nebula



Sulfer (S II, 673 nm) = red
Hydrogen Balmer-α (656 nm) = green
Oxygen (O III, 502 nm) = blue

Fraunhofer Lines

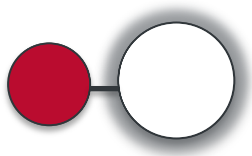


scale in Ångstrom; 1 Å = 0.1 nm

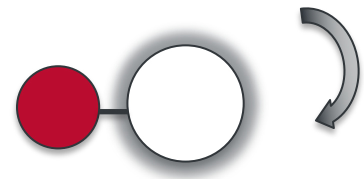
K & H: resonance lines of calcium ions
G: rotation-vibration band of CH molecules
F: Balmer-β line of hydrogen atoms
b: three lines of magnesium atoms
E: a group of lines of iron atoms
D: two resonance lines of sodium atoms (the same as in street lights)
C: Balmer-α line of hydrogen atoms
B & A: rotation-vibration band of oxygen molecules in the Earth atmosphere

Credit: Toon

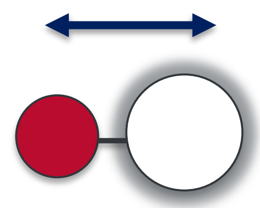
Molecules: More Quantitized Energy Levels



carbon monoxide (CO)



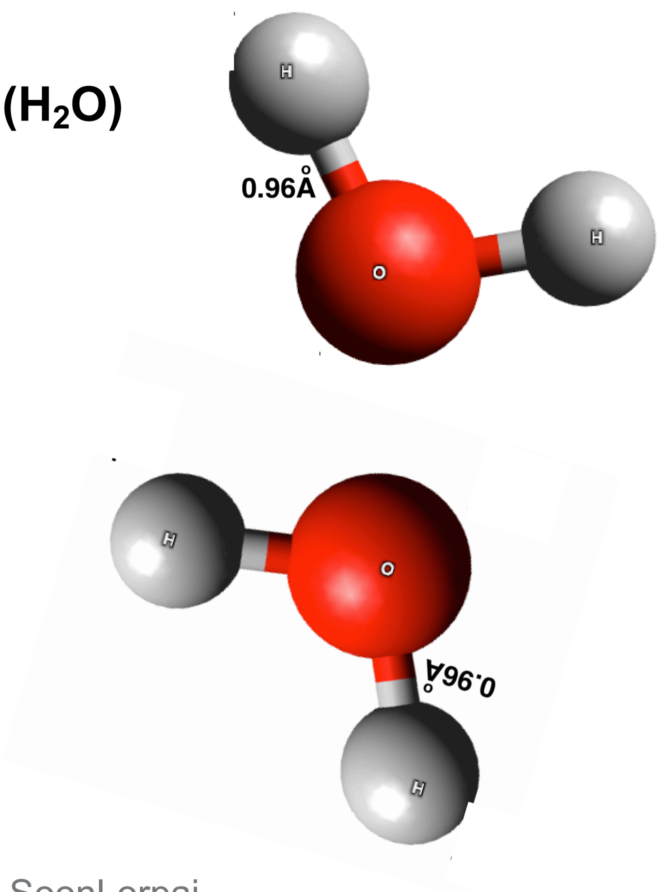
rotational transitions

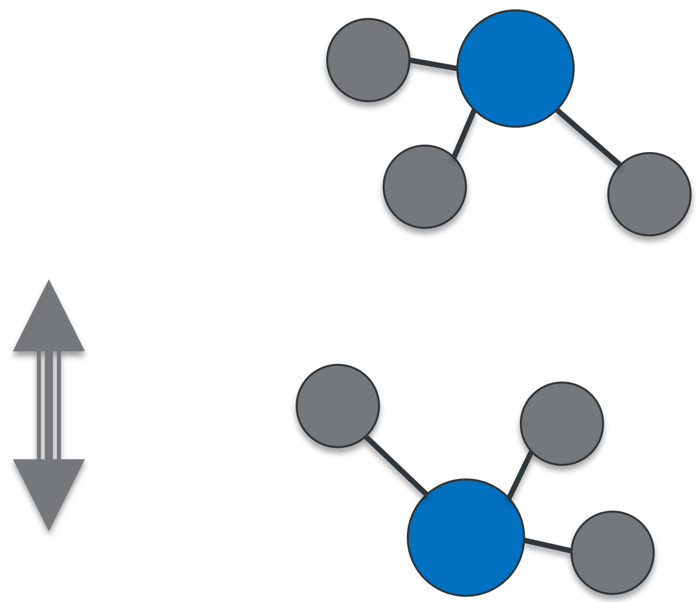


vibrational transitions

Molecules: More Quantitized Energy Levels

Water (H_2O)

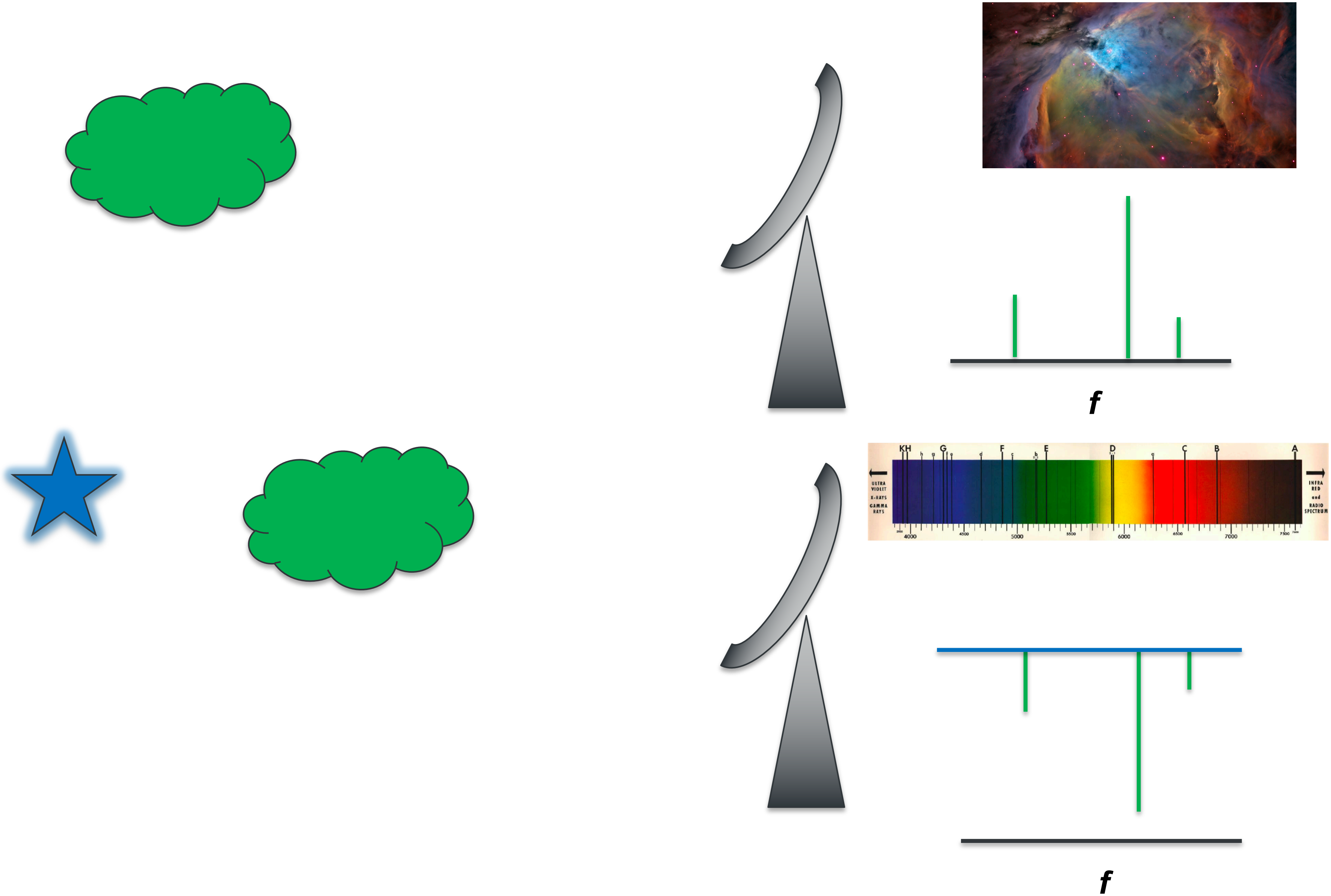




Ammonia (NH_3)

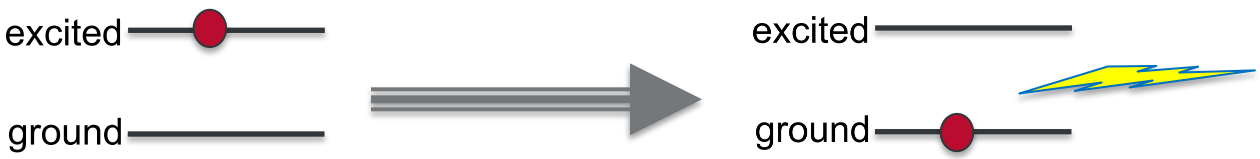
Credit: SoonLorpai

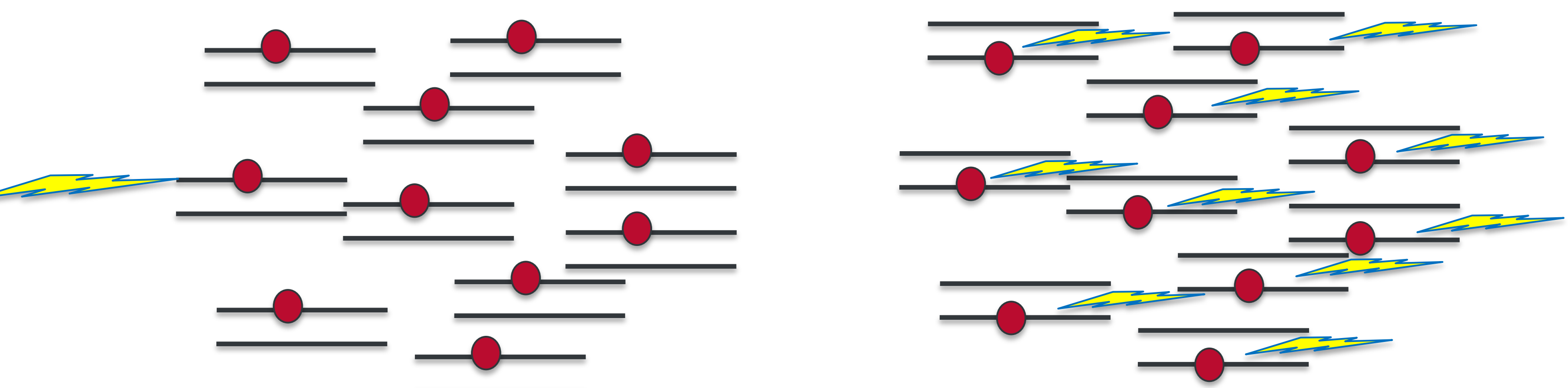
Emission and Absorption and …



… Stimulated Emission

… Amplification by the Stimulated Emission of Radiation



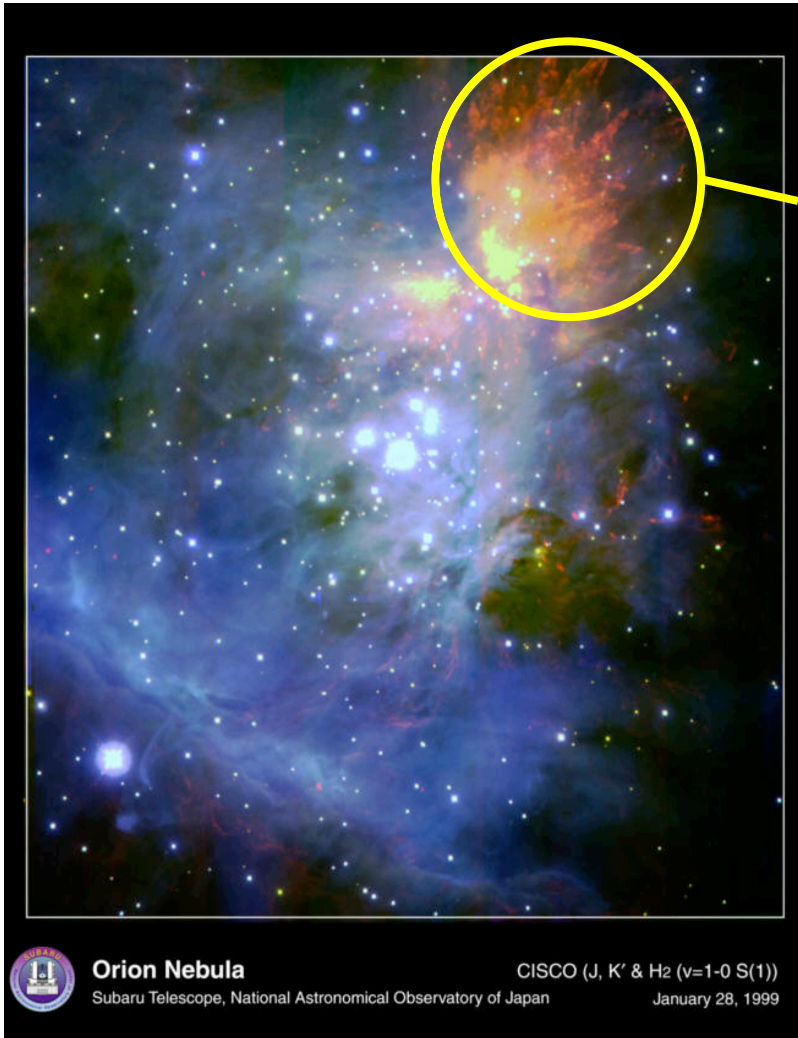


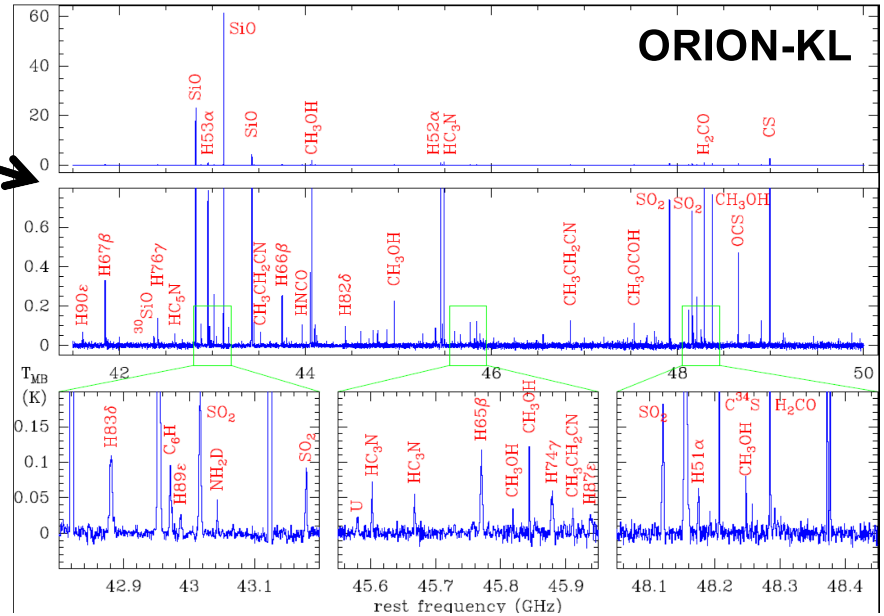
Light Amplification by the Stimulated Emission of Radiation (LASER)

Microwave Amplification by the Stimulated Emission of Radiation (MASER)

Orion Nebula

Molecular Line Emission



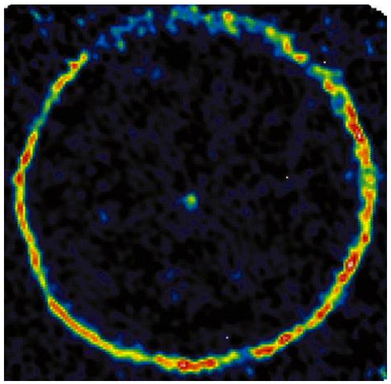


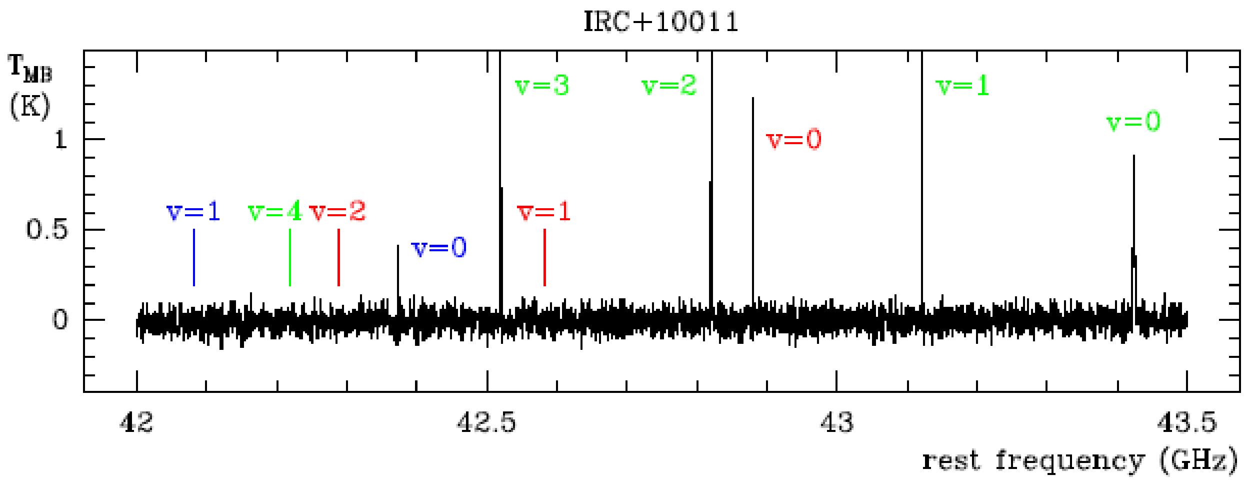
Rizzo et al. in preparation, **"The line emission of Orion-KL between 41 and 50 GHz"**

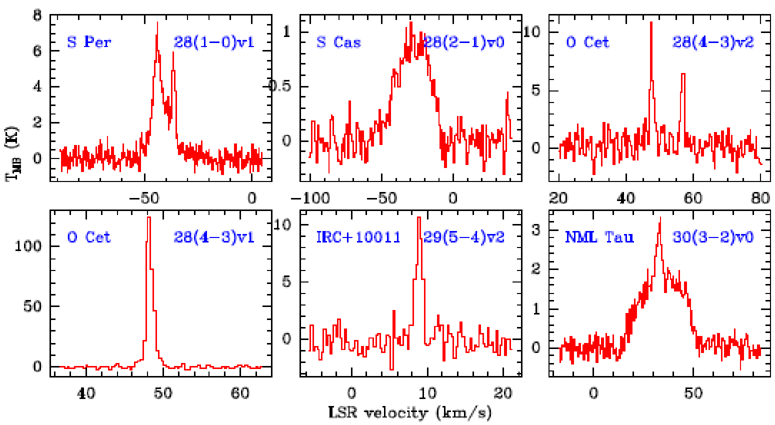
Most sensitive and widest spectrum of Orion KL between 6 and 7 mm. Obtained with Q-band receiver and wideband backend attached at DSS-54.

Evolved Star Survey

Molecular Line Emission





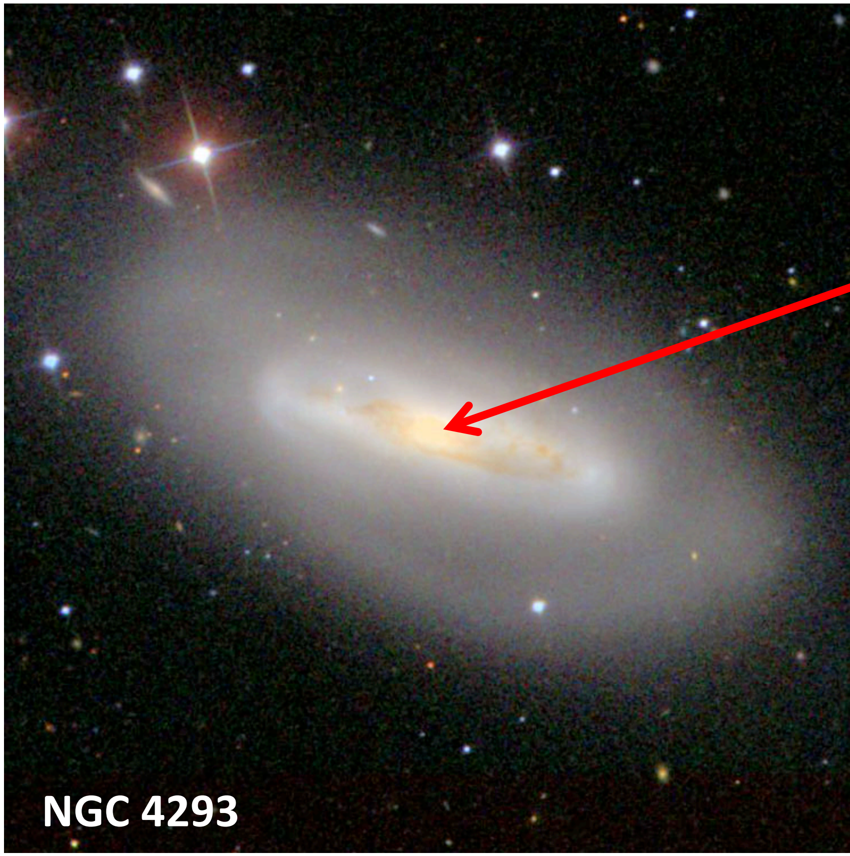


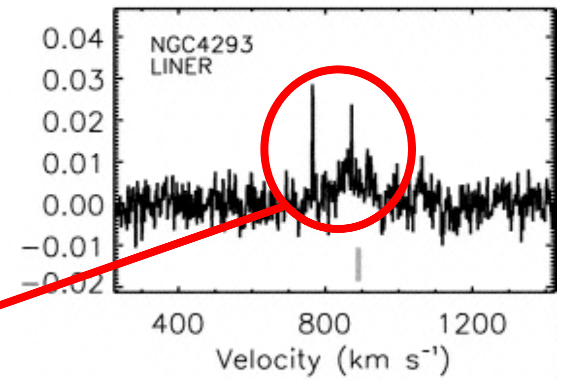
SiO Q-band survey of 67 O-rich evolved stars with 66 transitions … 1525 spectra!!

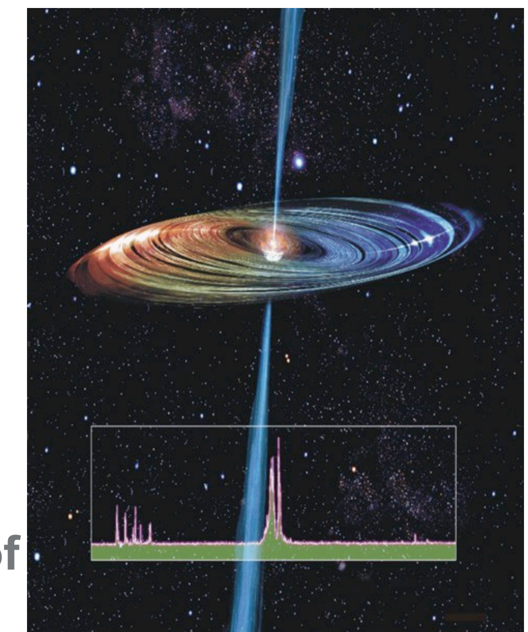
Rizzo, Garcia-Miro et al. in preparation, "SiO, ^{29}SiO, and ^{30}SiO emission from O-rich stars: I. A survey of 61 rotational lines from 7 to 1 mm"

Hunting for Supermassive Black Holes

Molecular Line Stimulated Emission (MASER)







Kondratko, et al. “Discovery of Water Maser Emission in Eight AGNs with 70 m Antennas of NASA's Deep Space Network,” ApJ, 638

Interstellar Chemistry

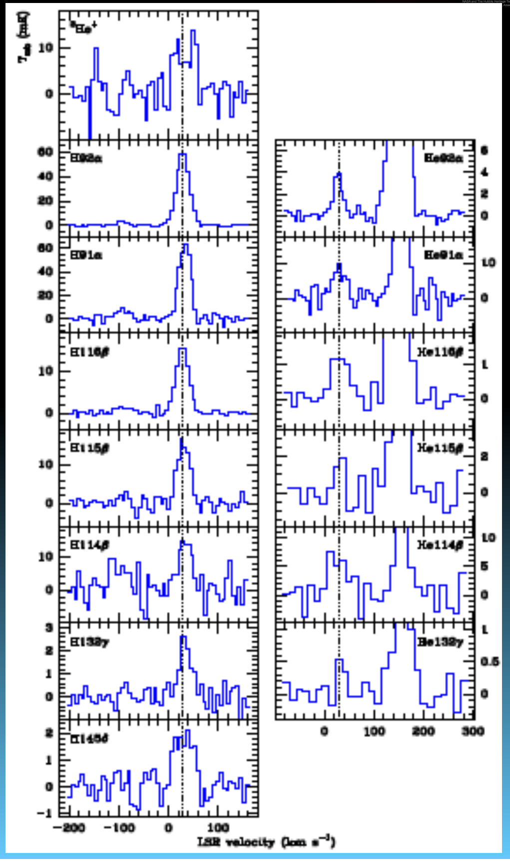
Atomic Line Emission

First Detection of $^3He^+$ in the Planetary Nebula IC 418

Stars like the Sun should produce lots of ^{3}He

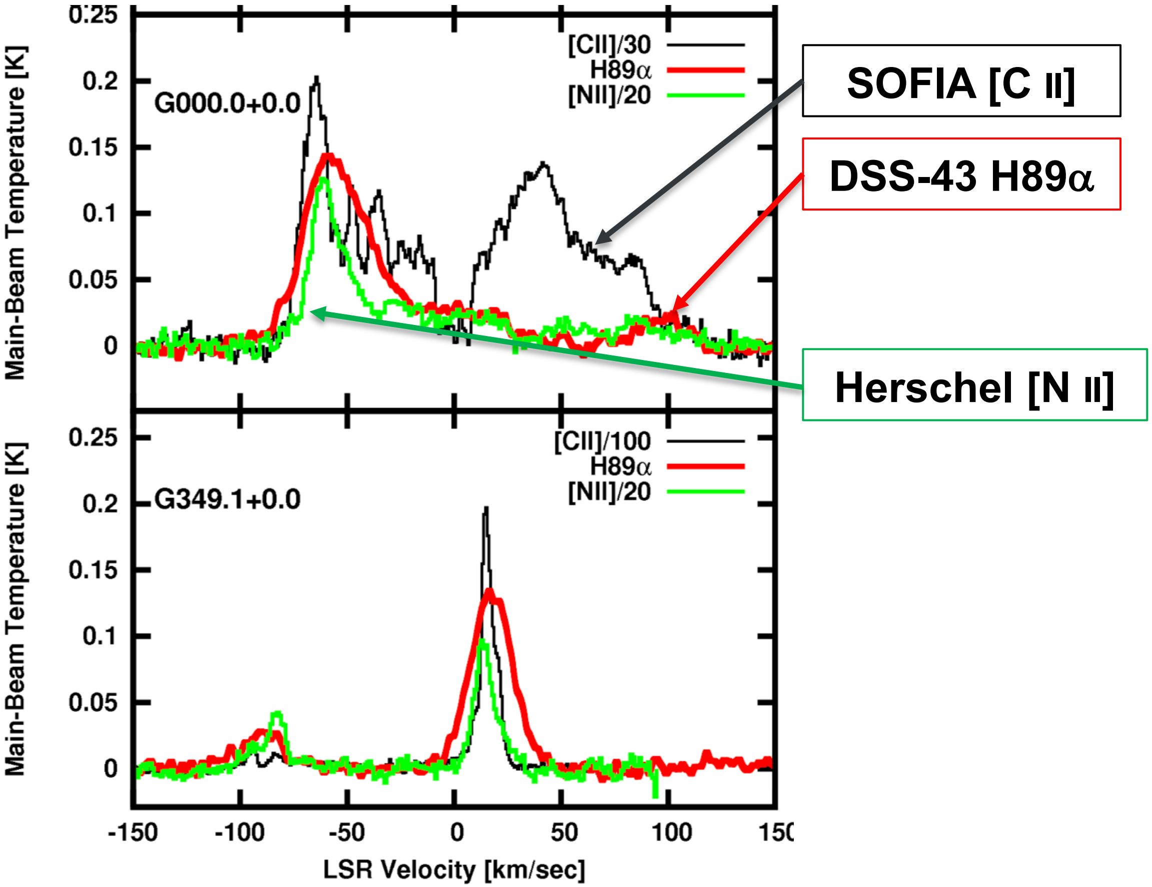
Less ^{3}He detected than expected

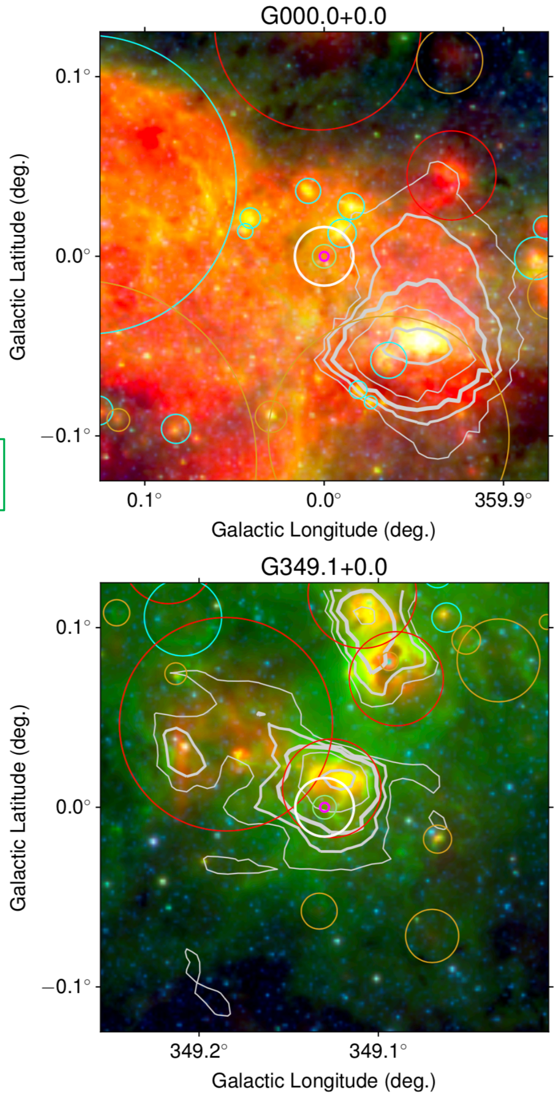
- **Planetary Nebulae offer chance to check how much ^{3}He made by low-mass stars**
- **Only 3rd detection of $^3He^+$ in planetary nebulae, by Madrid DSN antenna**



Guzman-Ramirez et al.

Interstellar Gas Cloud Properties





Pineda et al. 2019

Radio Astronomy

Large radio antennas, equipped with sensitive (cryogenic) microwave receivers

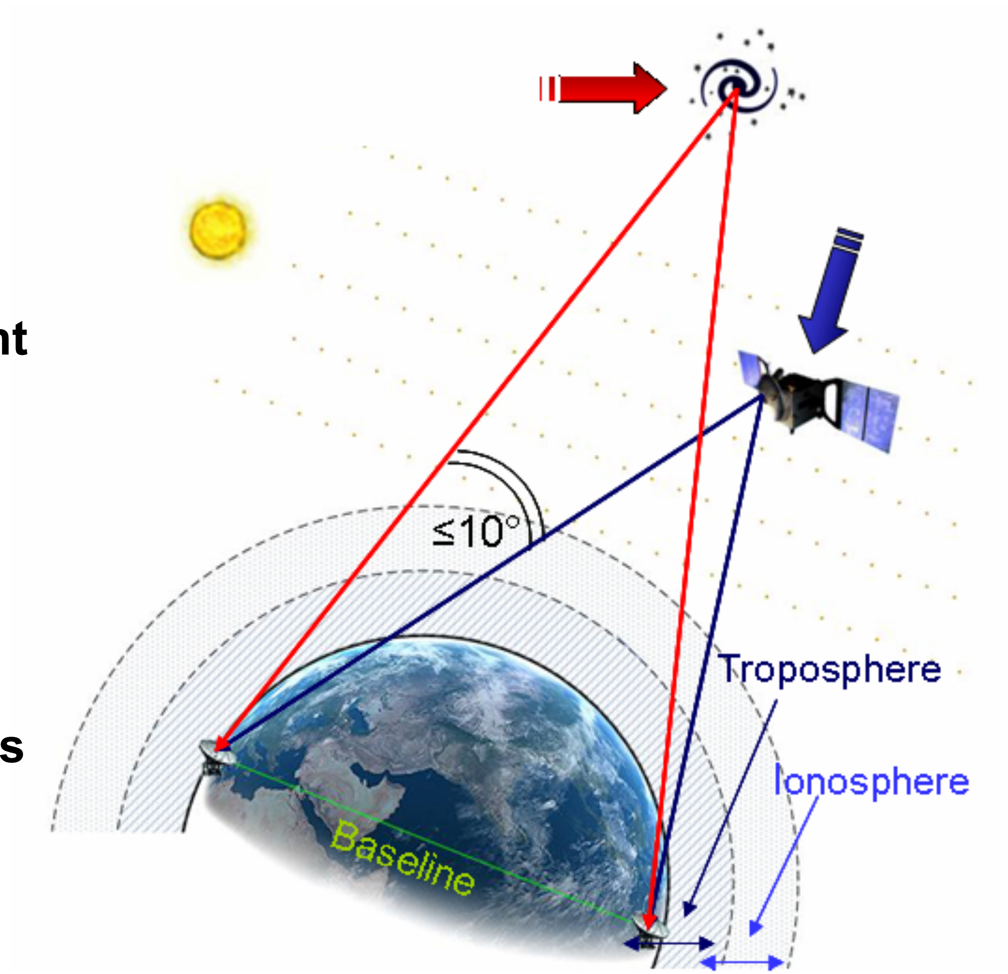
- **Spectroscopy**
  - **Complements ALMA, complements NASA and ESA far-infrared—sub-millimeter missions (e.g., Planck, *Herschel*, SOFIA)**
- **Very Long Baseline Interferometry (VLBI)**
  - **Complements VLBA, EVN, LBA; many NASA and ESA mission complements**
- **Time Domain**
  - **Many NASA and ESA mission complements**

Spacecraft Navigation

ΔDOR (Delta-Differential One-Way Range)

ΔDOR provides Plane-of-Sky information

- **Complementary to line-of-sight from Doppler and range**
- **Essential beyond lunar distance**
- **Optical analogy is called "Optical Astrometry"; uses star catalog instead of quasars**



Historical Background

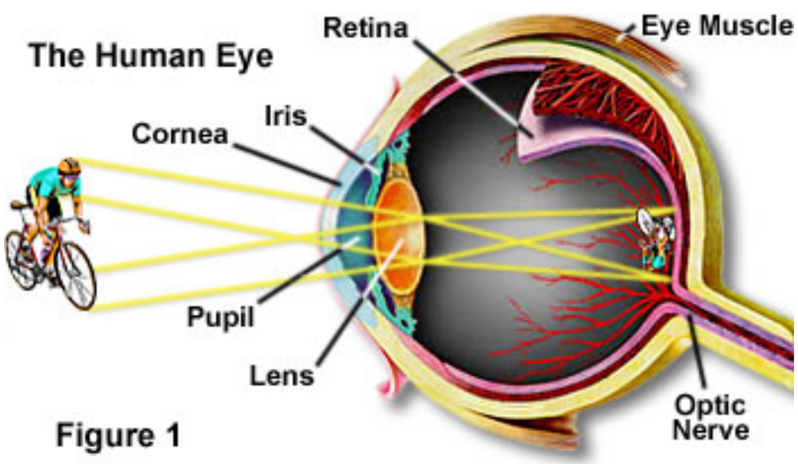
Pre-20th Century

Human eye capable of diffraction-limited imaging of about 1 arcminute

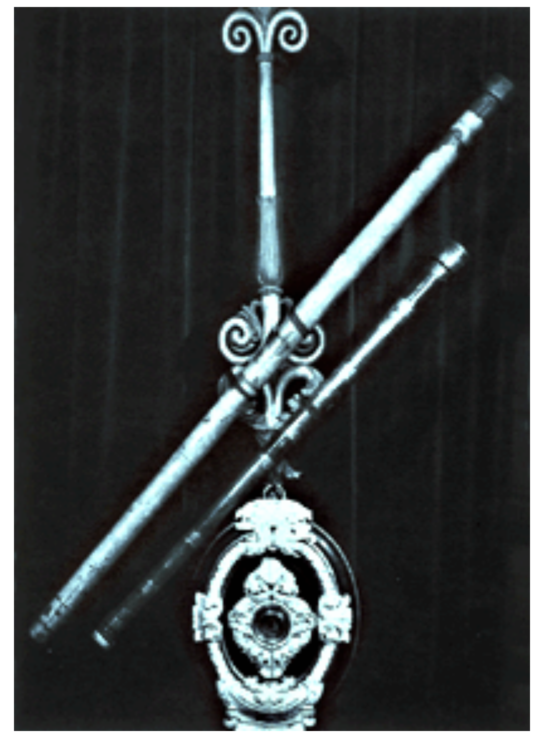
- **20/20 vision ~ U.S. quarter across football pitch**

Modest optical telescopes provide diffraction-limited imaging at 1 arcsecond resolution

- **60× better**

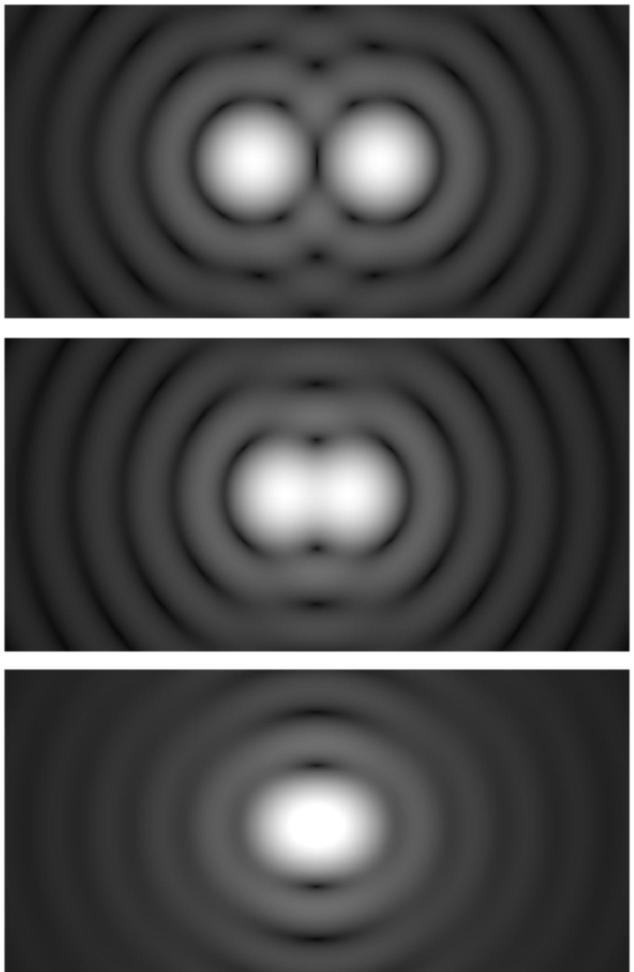


Credit: Micael W. Davidson, (Florida State Univ.)



Angular Resolution and Optics

Can Two Stars Be Split?



Credit:
Spencer Bliven

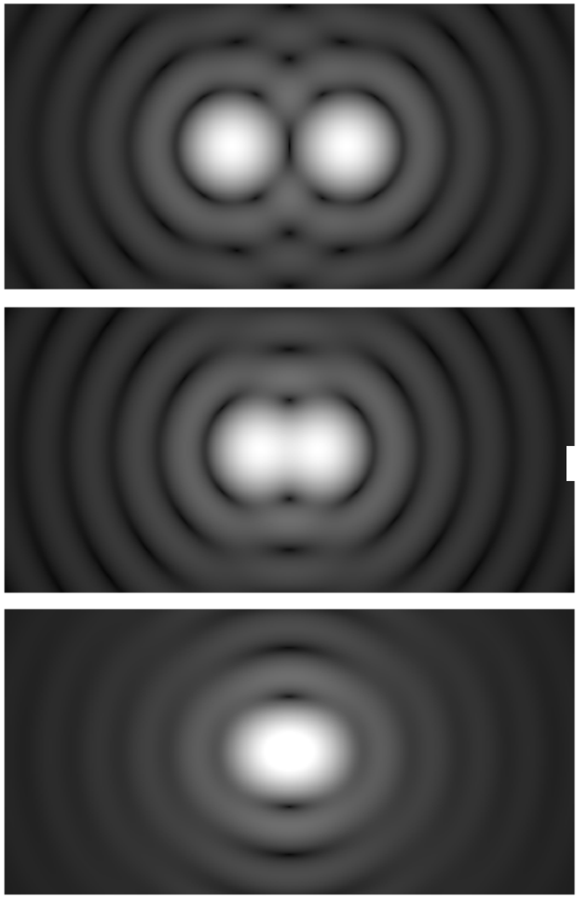
Fundamental optics

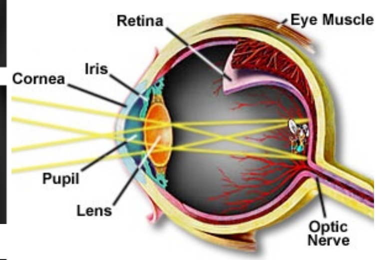
$$\theta = \lambda/D$$

- **λ = observing wavelength**
- **D = diameter of aperture**

Angular Resolution and Optics

Human Eye





- λ **~ 550 nm (~ 0.00055 mm)**
  - **observing wavelength**
  - **green-yellow light**
- **D ~ 5 mm**
  - **diameter of pupil (aperture)**

✓ **θ ~ 0.00011 radians ~ 0.0063° ~ 0.4 arcminutes**

$\theta = \lambda / D$

Angular Resolution and Optics

Radio Telescopes

- λ ~ 0.30 m (~ 1 GHz)
- D ~ 300 m

  diameter of telescope

➢ θ = 0.001 radians ~ 0.06° ~ 3 arcminutes

  $\theta = \lambda/D$

! Your eye has higher angular resolution than Arecibo telescope!

Angular Resolution and Optics

Radio Telescopes

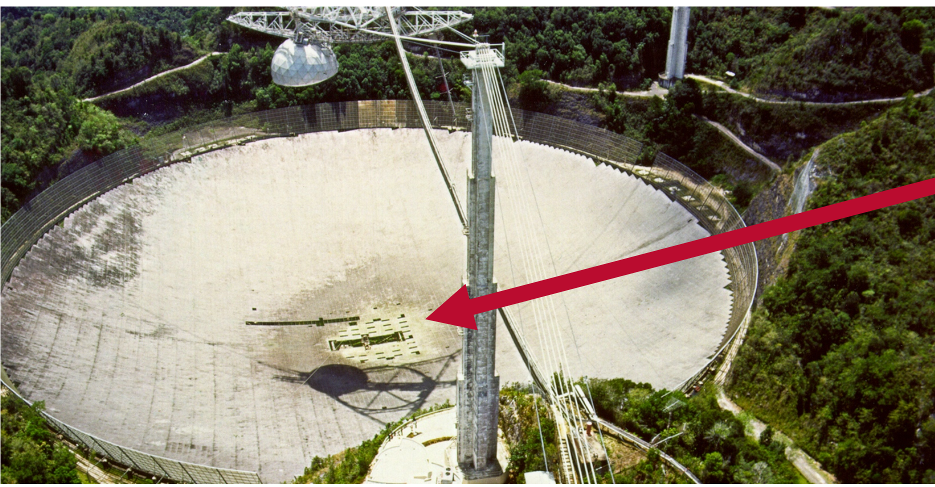
Arecibo diameter ~ 300 m

?? **Match angular resolution of human eye ~ 1 km**

?? **Match angular resolution of modest visible wavelength telescope ~ 10 km**

Angular Resolution and Optics

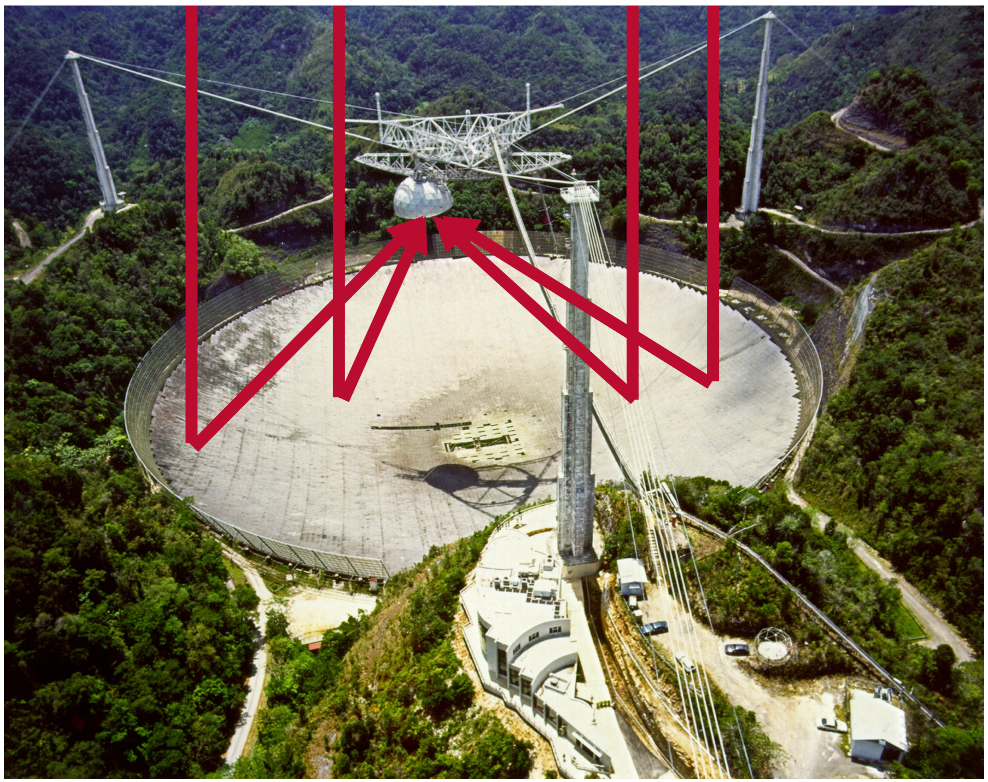
Radio Telescopes



Arecibo has hole in its middle!

How many holes can a telescope have and still work?

How Do Telescopes Work?



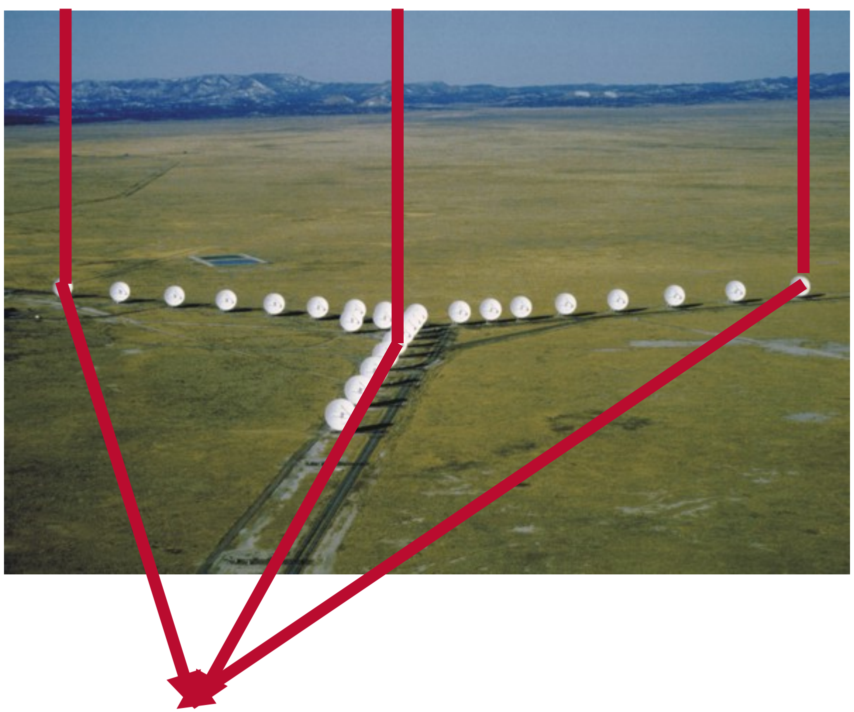
Exercise for the reader:

Consider a parabolic surface.

Show that initially parallel light rays, all traveling at the speed of light *c*, reach a common point, *the focus*, at the same time no matter where they reflect from the surface of the reflector.

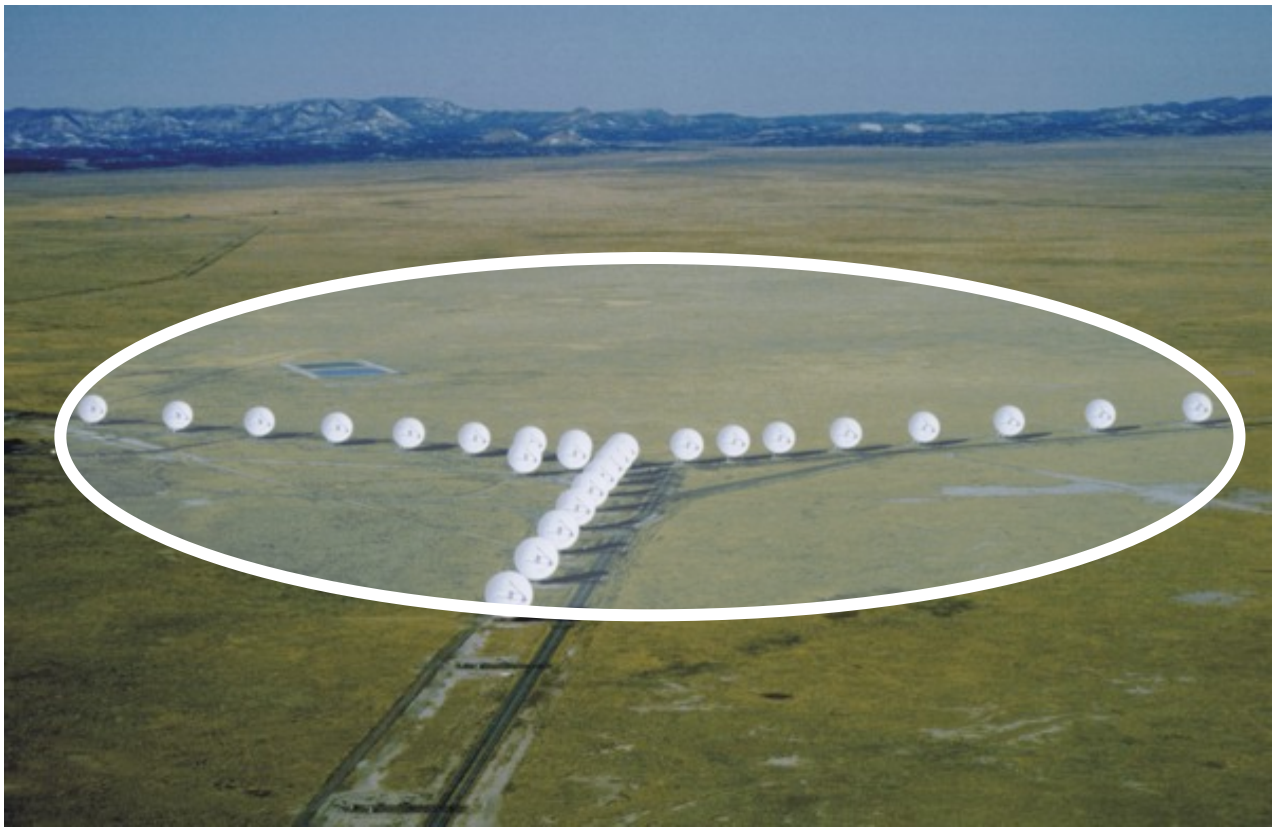
Extra credit: Repeat for a spherical reflector such as Arecibo and show that the focus is a line.

Aperture Synthesis



1. Record signals at individual antennas
2. Bring them together “at the same time” (coherently)
3. Then …

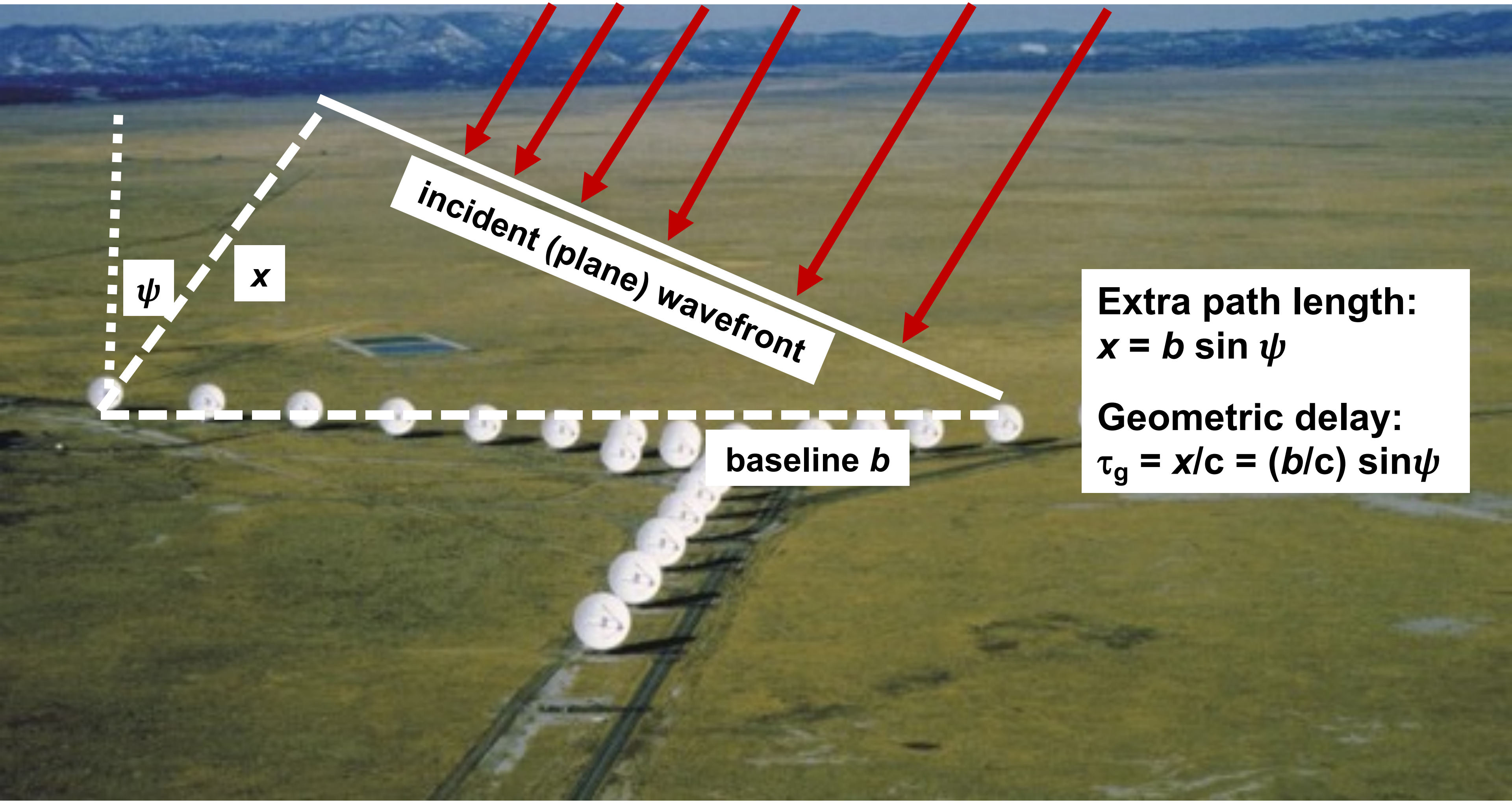
Interferometry or Aperture Synthesis



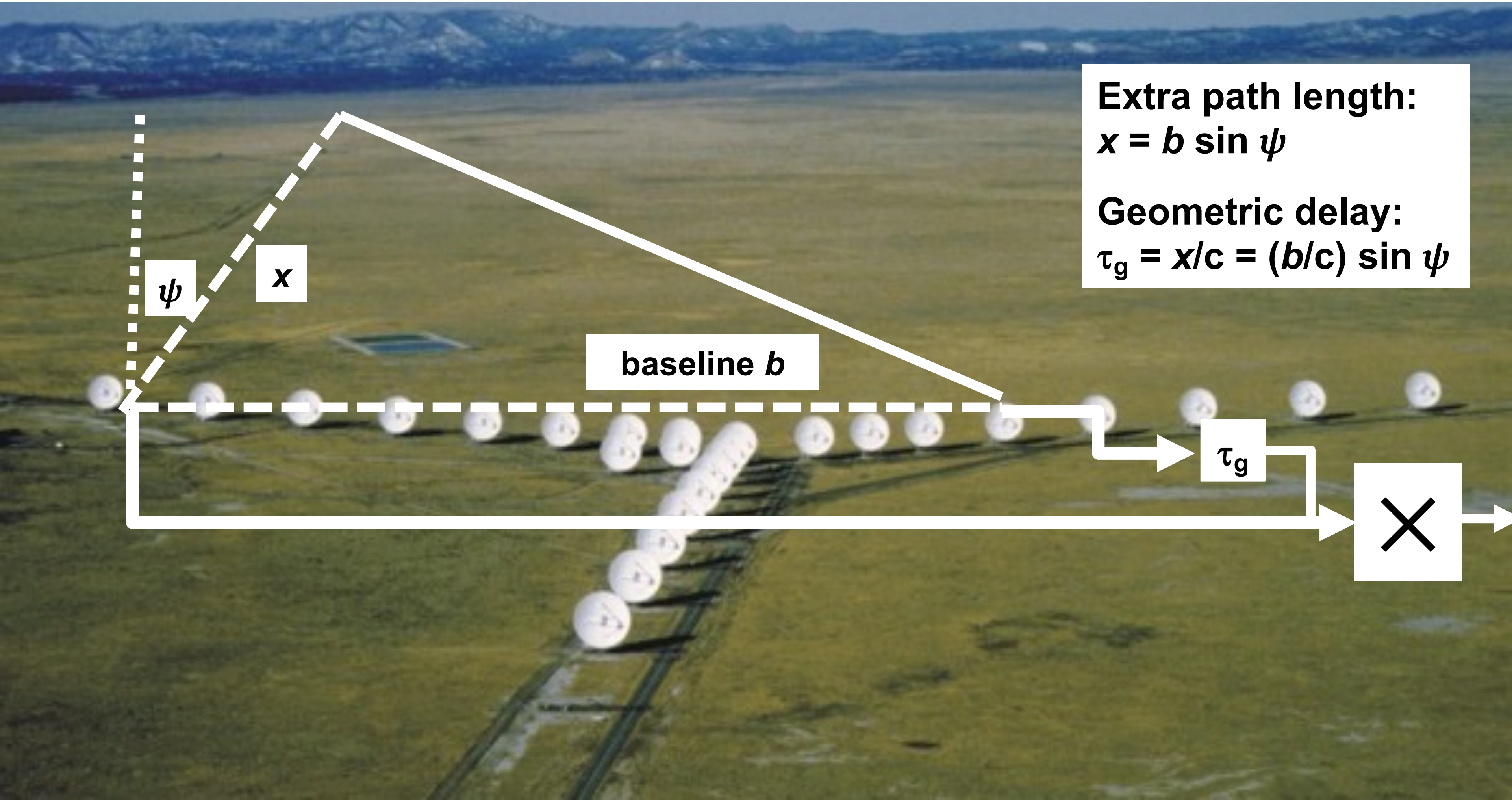
1. Record signals at individual antennas
2. Bring them together "at the same time" (coherently)
3. Synthesize aperture!

   a.k.a. build telescope that's mostly holes!

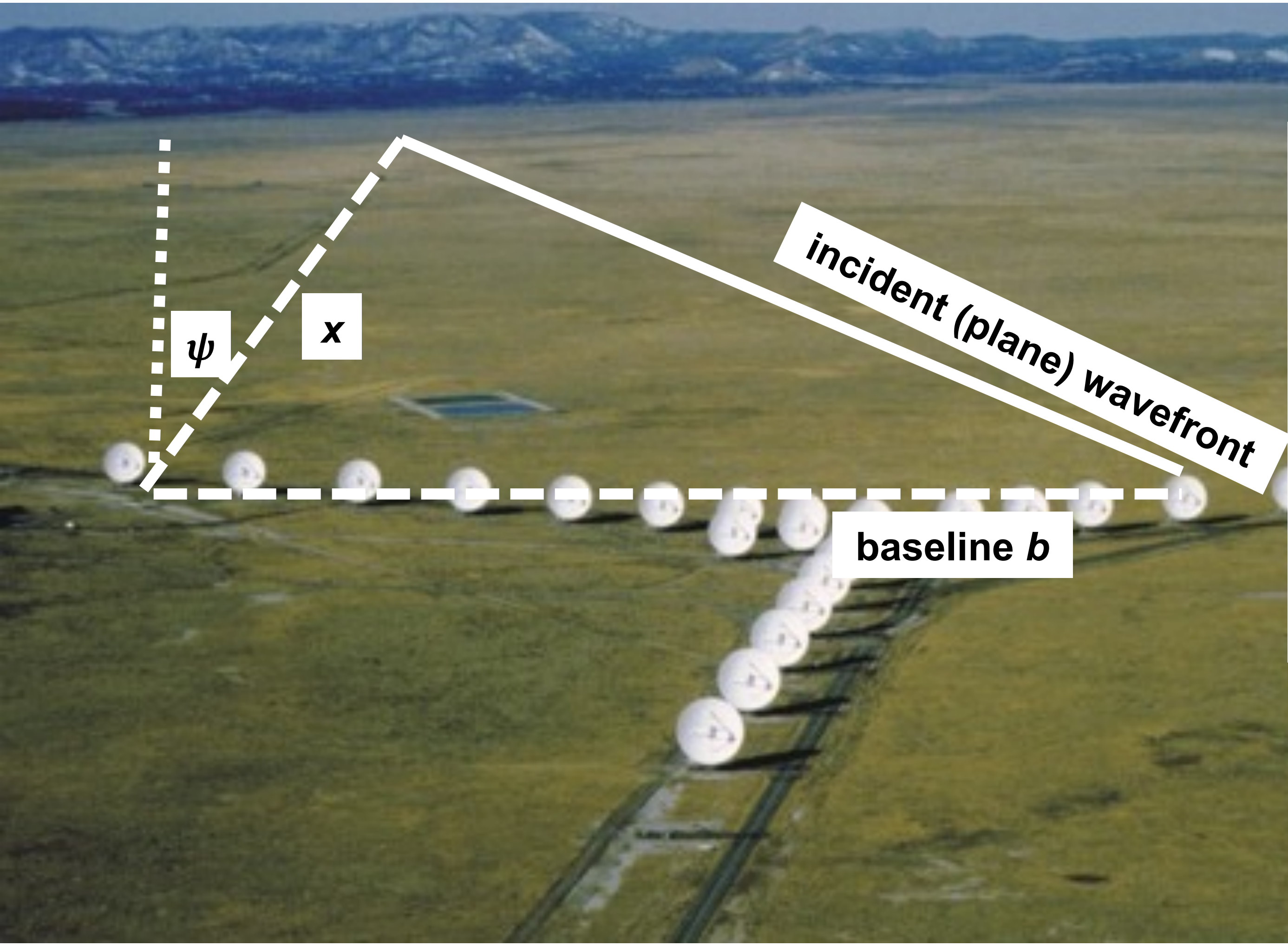
Aperture Synthesis



Aperture Synthesis



Aperture Synthesis



Geometric delay:
$\tau_g = x/c = (b/c) \sin \psi$

Need to know where antennas are

- ***Knowledge*, not control**
- **Only *relative* positions**

Van Cittert-Zernike Theorem

Formal:

$$\Gamma(u,v) = V(u, v) = \int I(\ell, m)e^{-2\pi i(u\ell + vm)}\, d\ell\, dm$$

Fourier Transform

Sky brightness

Mutual coherence function
a.k.a.
Visibility function

Assumptions

Narrow field of view

Co-planar array

Monochromatic signals (narrow bandwidths)

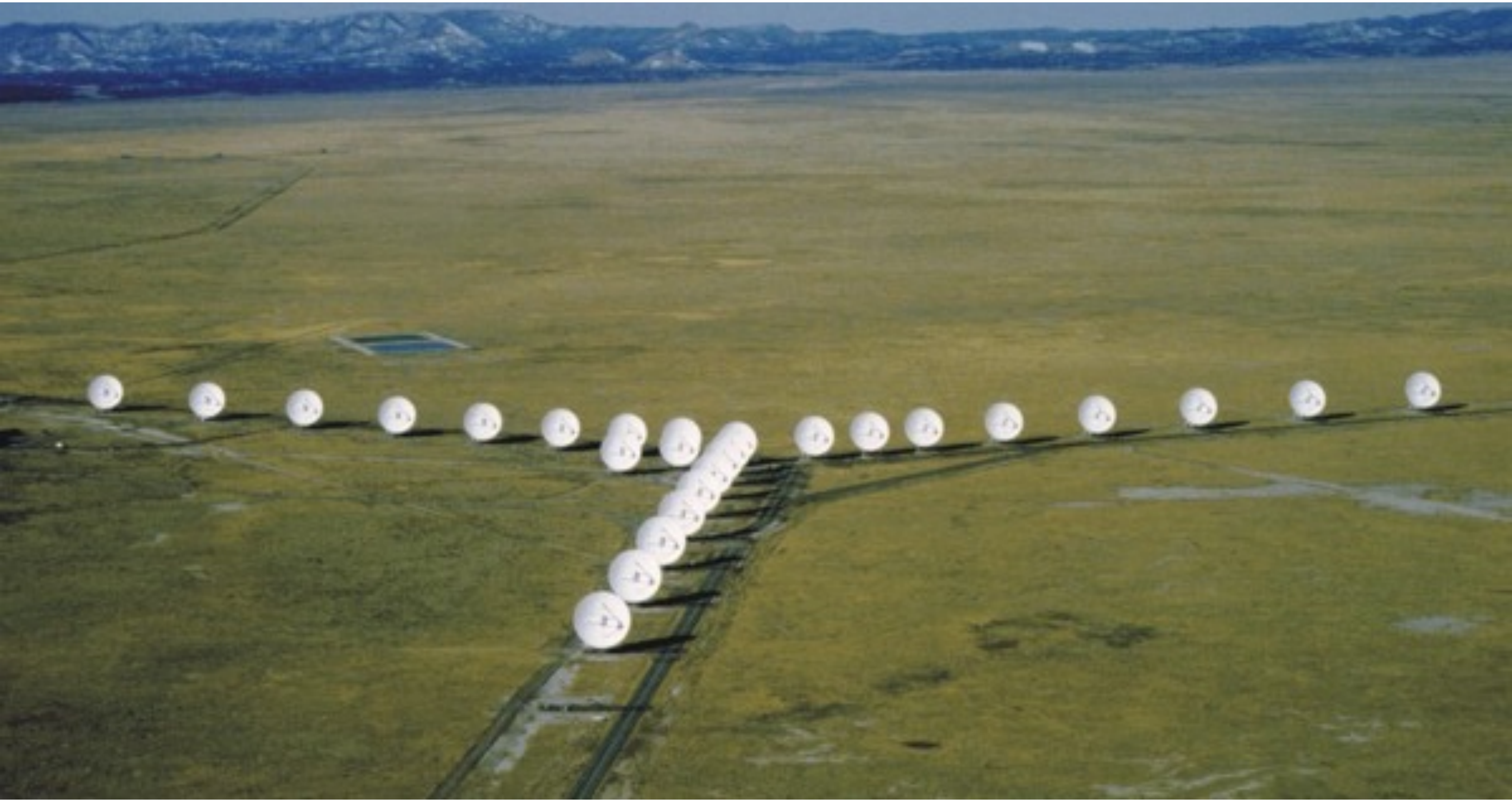
Instantaneous signal reception

Aperture Synthesis

1974 Nobel Prize in Physics

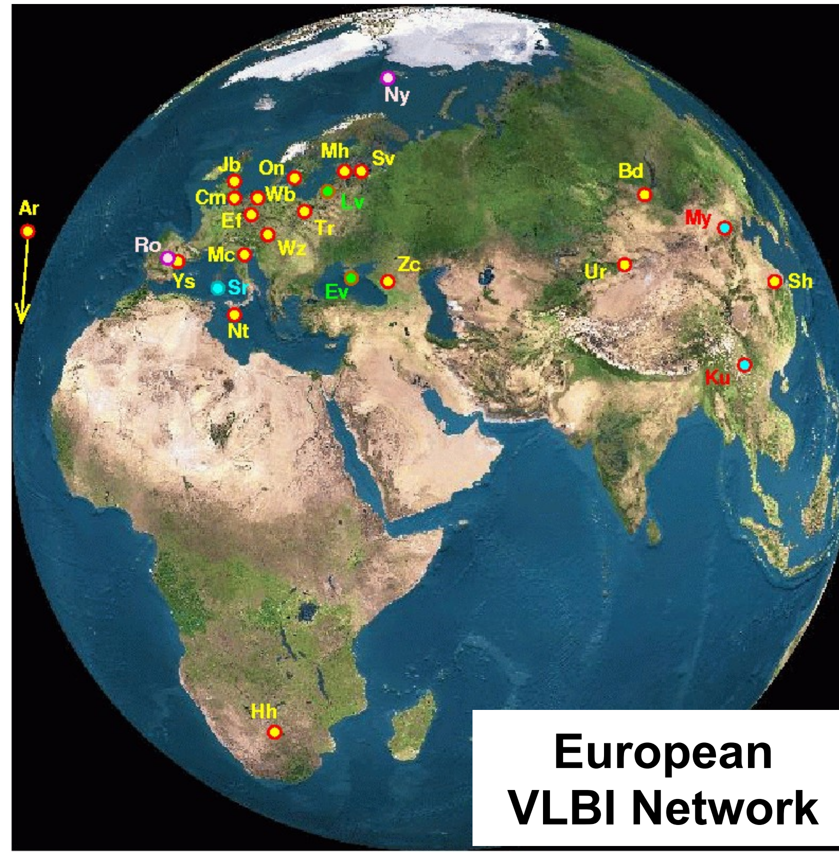
The Nobel Prize in Physics 1974 was awarded jointly to Sir Martin Ryle and Antony Hewish "for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars."

Very Large Array



Very Long Baseline Interferometry

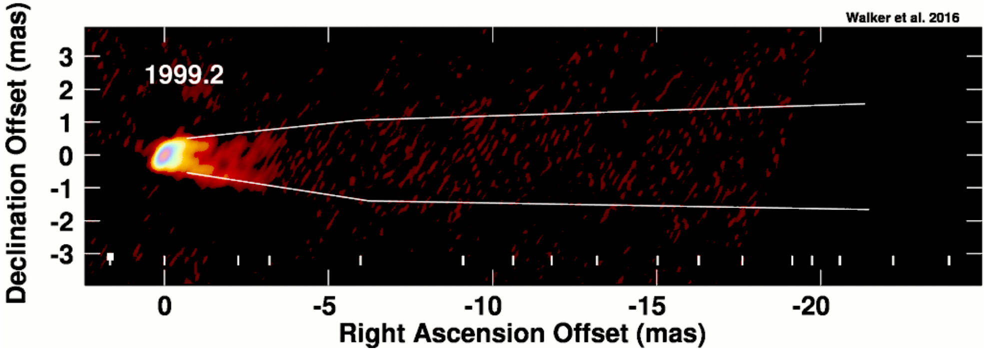
Very Long
Baseline Array



European
VLBI Network

How Small Can Radio Sources Be?

Space-based Interferometry



- **By mid-1970s, clear that some radio sources still unresolved on terrestrial baselines**
- **Also superluminal motion**
- **Heuristically, if source too small, energy density not enough to be visible to terrestrial radio interferometers?**
  - **A.k.a. no free lunch theorem**

    As synthetic apertures, interferometers limited to observing bright sources, because telescope with lots of holes
  - **Inverse Compton catastrophe**

Space Interferometry

From Science, 1986 October 10. Reprinted with permission from AAAS.

"Very Long Baseline Interferometric Observations Made with an Orbiting Radio Telescope" (Levy et al., 1986 October 10)

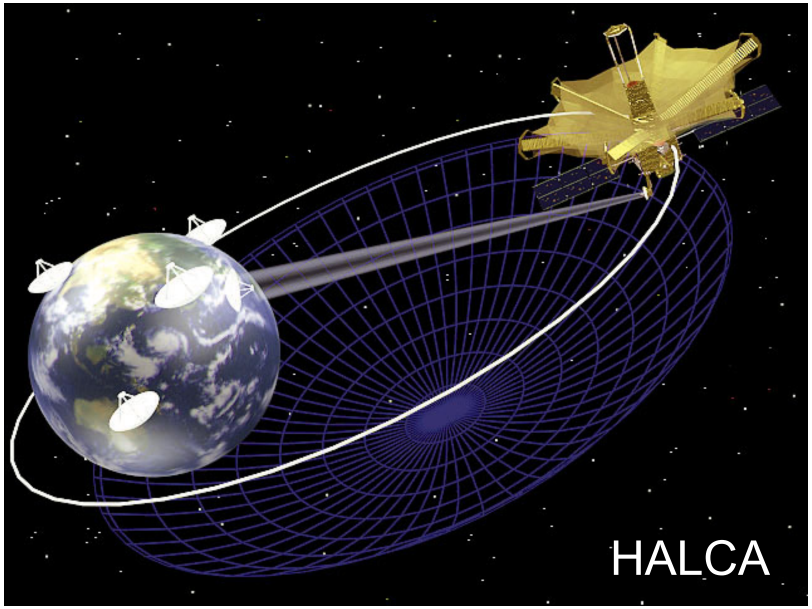
TDRSS-E + DSS-43 + Usuda

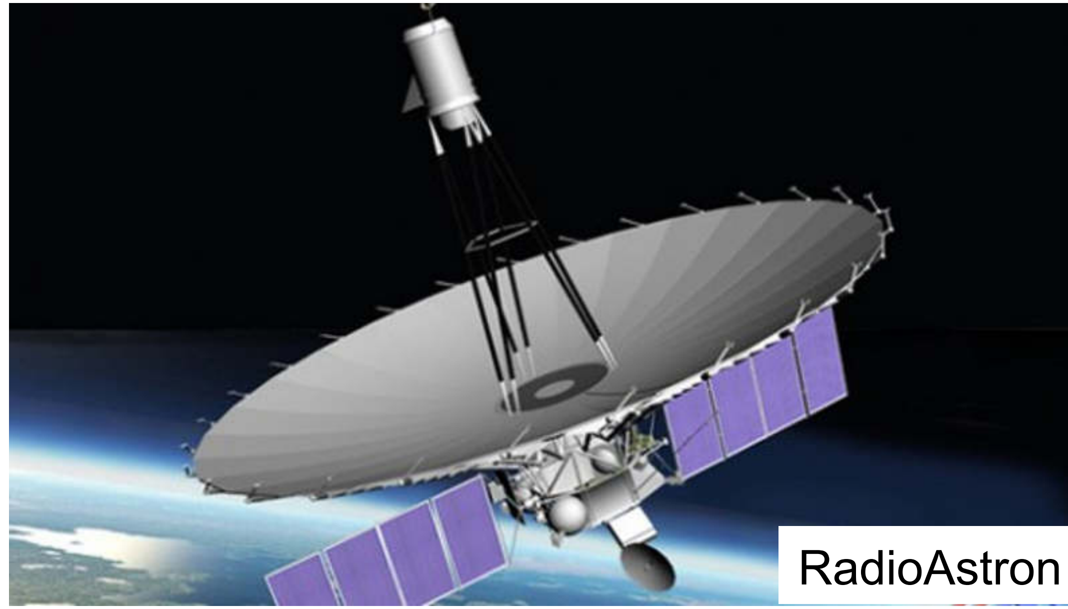
4.9 m-diameter TDRSS antenna

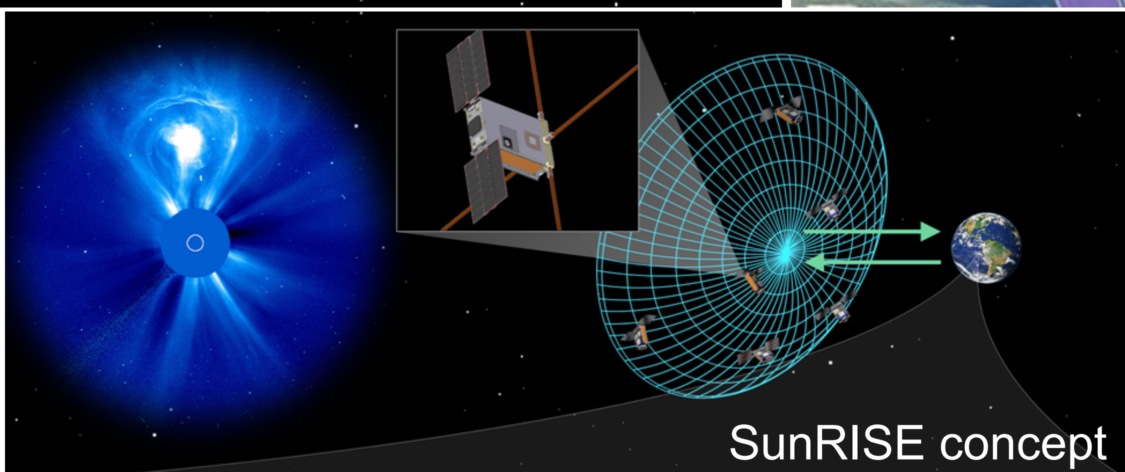
64 m-diameter Canberra DSCC

64 m-diameter ISAS antenna

Space Interferometry



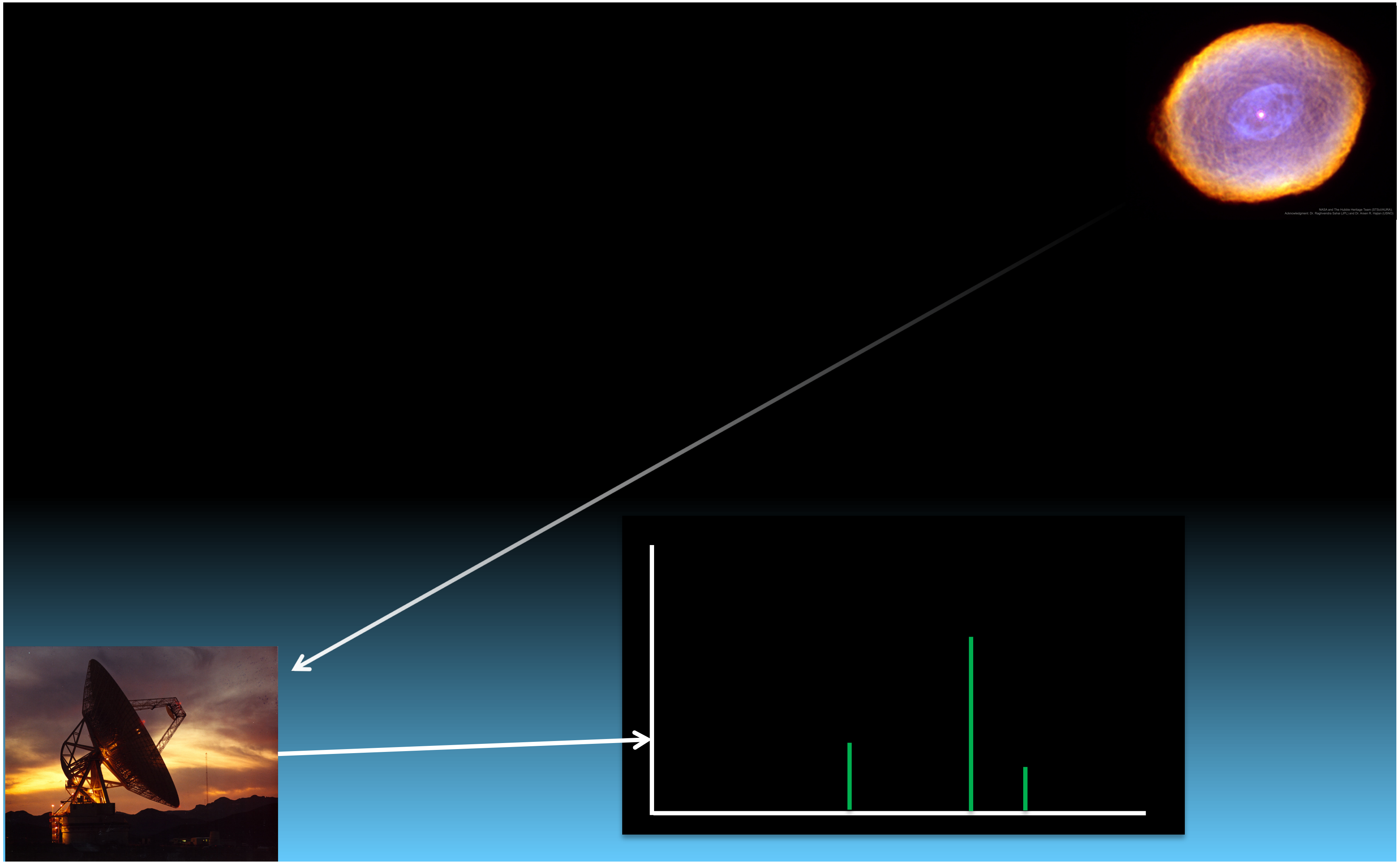




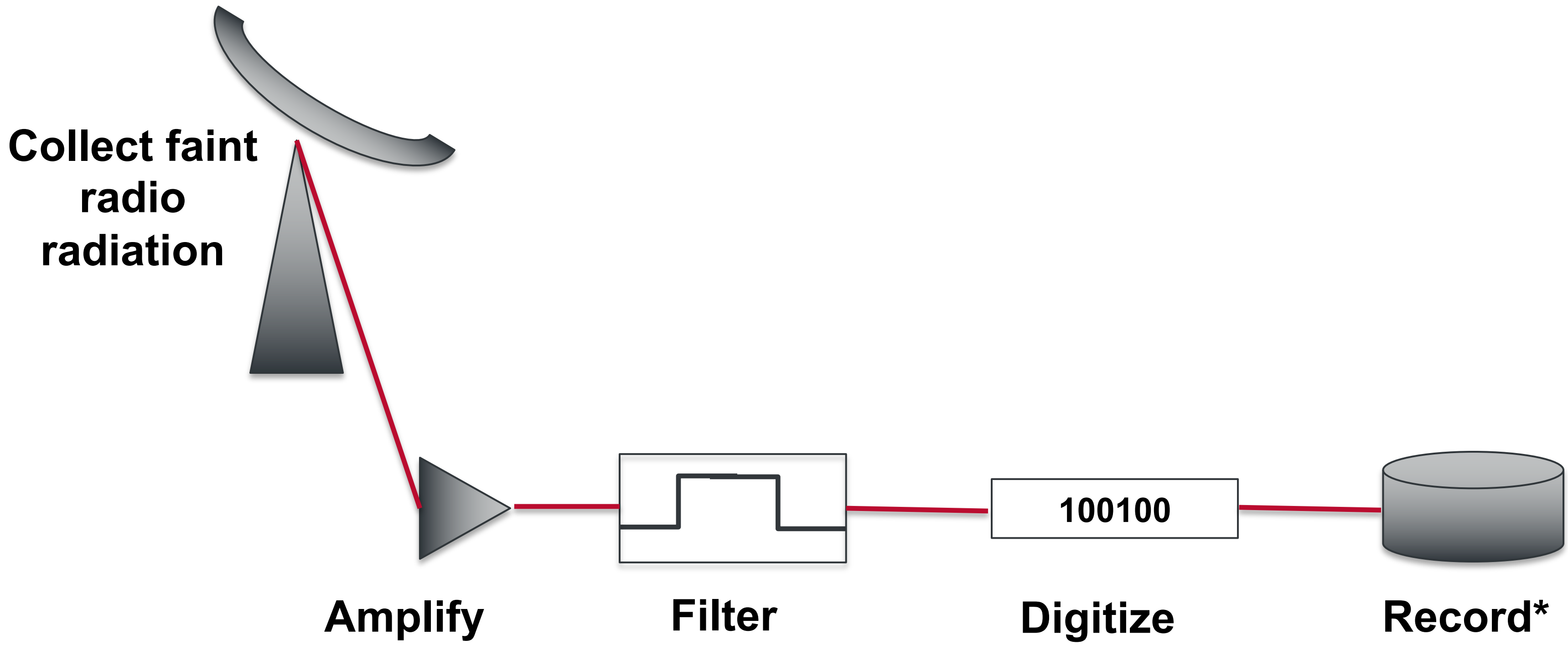
Millimeter-wave space-based VLBI?
(Event Horizon Telescope to Event Horizon Imager)

Radio Astronomy

Conceptual Radio Telescope

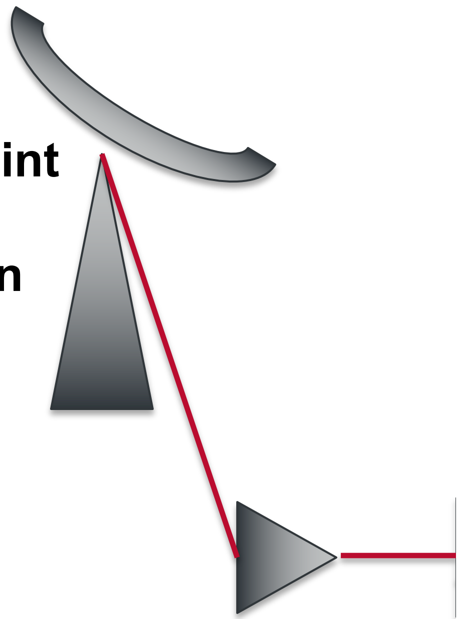


Conceptual Radio Telescope



*Today: Record to hard drive disk packs or even direct streaming across the Internet
Historical note: Record on magnetic tapes, including VHS tapes

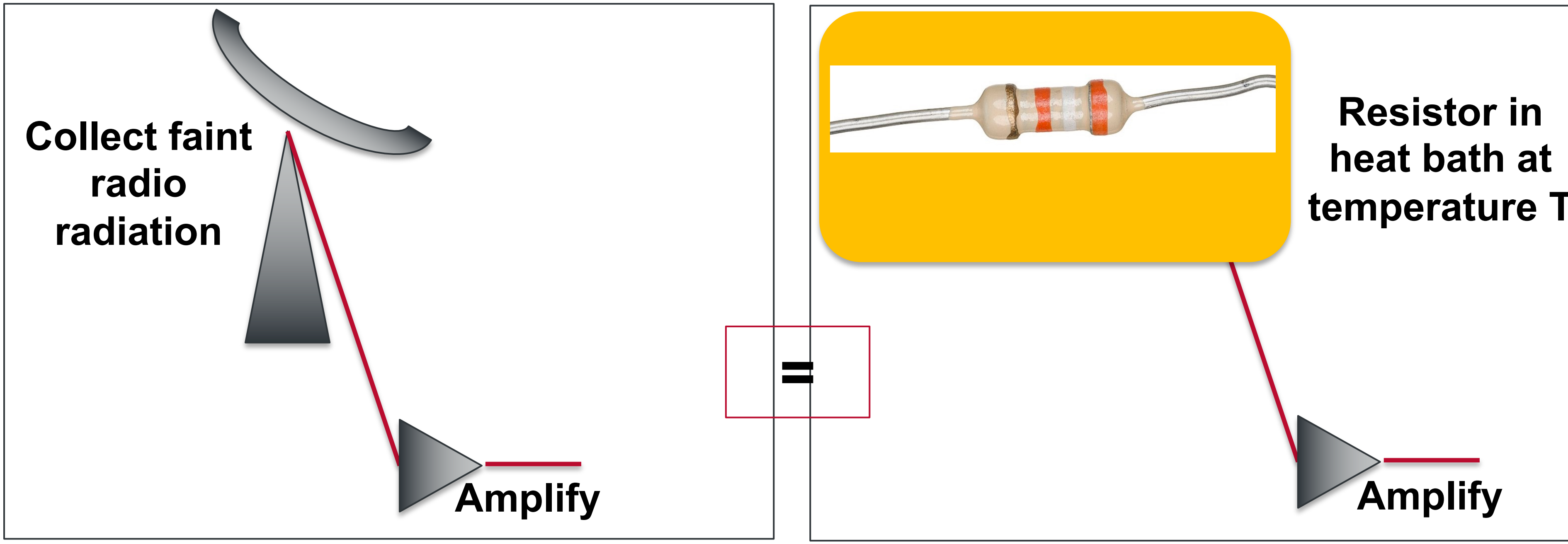
Conceptual Radio Telescope



Amplify

- Signals are faint!
- Need to provide sufficient power for input to following stages of signal processing
- Typical levels of gain might be 30 dB (1000×) or more
- Typically *cryogenic* to reduce "noise"
  - Use low noise amplifiers (LNAs)
  - Maintain at 77 K or lower

“Noise”



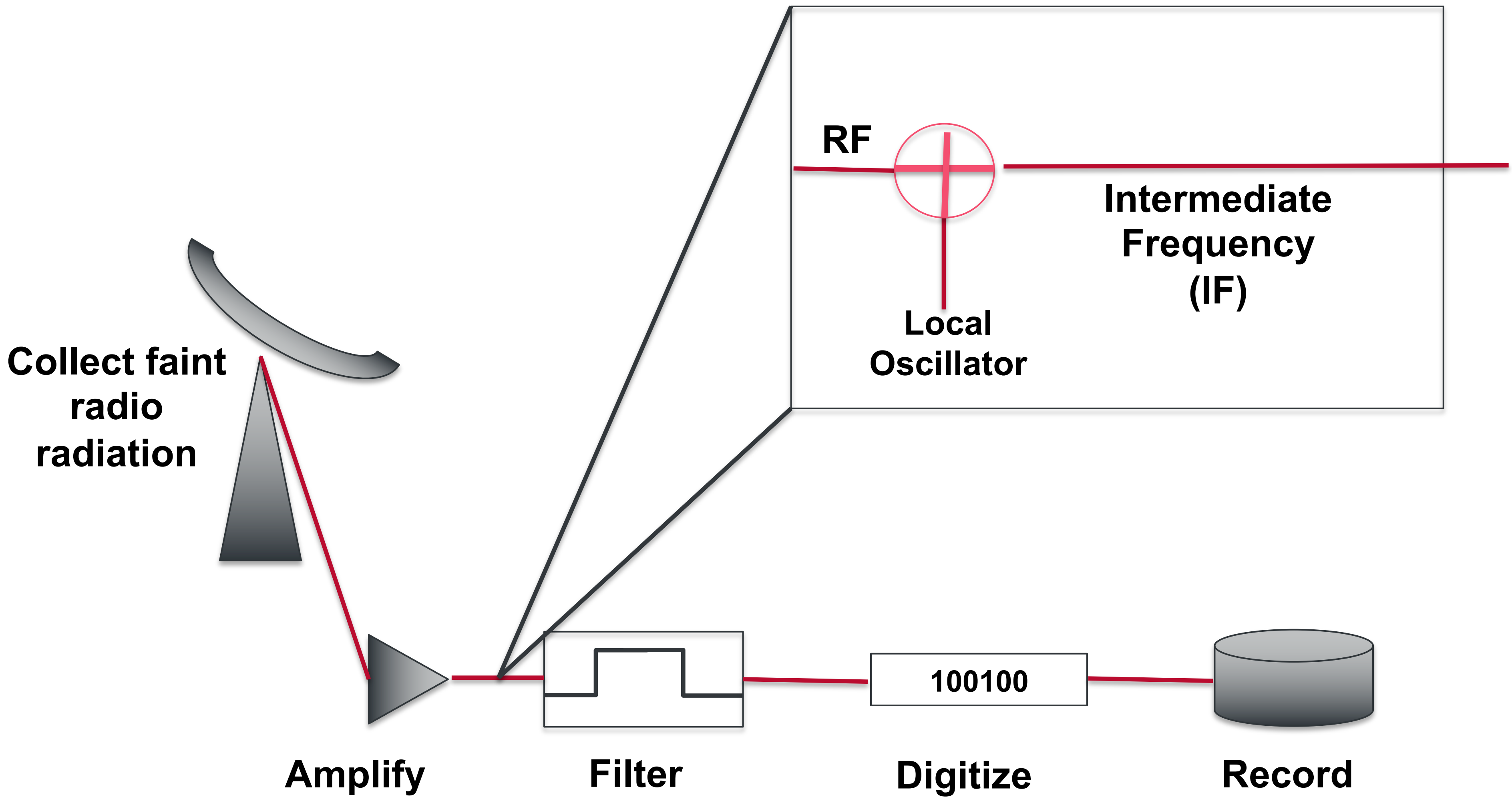
- **Thermodynamic equivalent between noise and power**

$$P = k_B T \Delta\nu$$

$k_B = 1.38 \times 10^{-23}$ J/K
$\Delta\nu$ = bandwidth

Conceptual Radio Telescope

Frequency Conversion

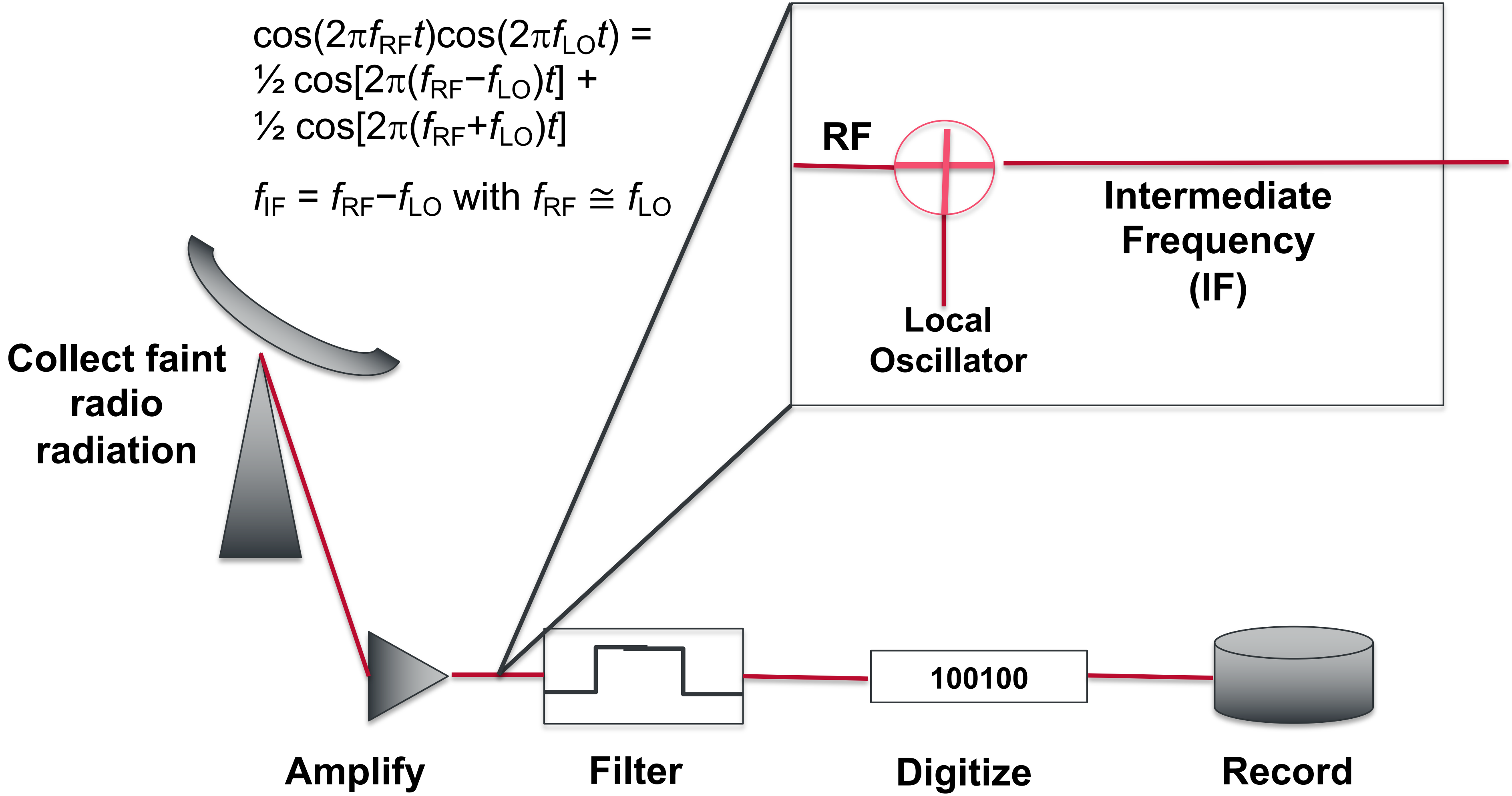


Conceptual Radio Telescope

Frequency Conversion

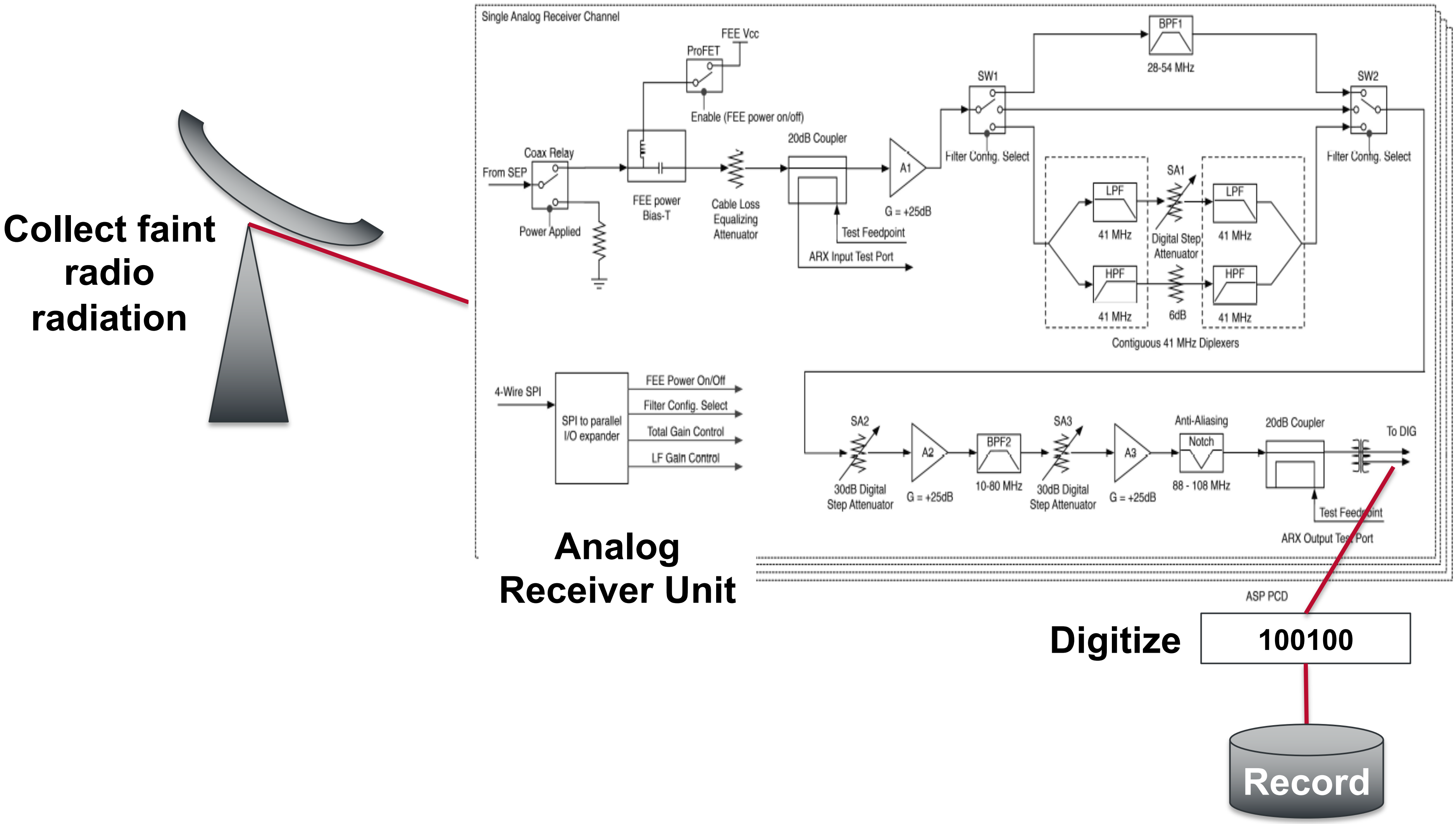
$\cos(2\pi f_{RF} t)\cos(2\pi f_{LO} t) =$
$\frac{1}{2}\cos[2\pi(f_{RF} - f_{LO})t] +$
$\frac{1}{2}\cos[2\pi(f_{RF} + f_{LO})t]$

$f_{IF} = f_{RF} - f_{LO}$ with $f_{RF} \cong f_{LO}$

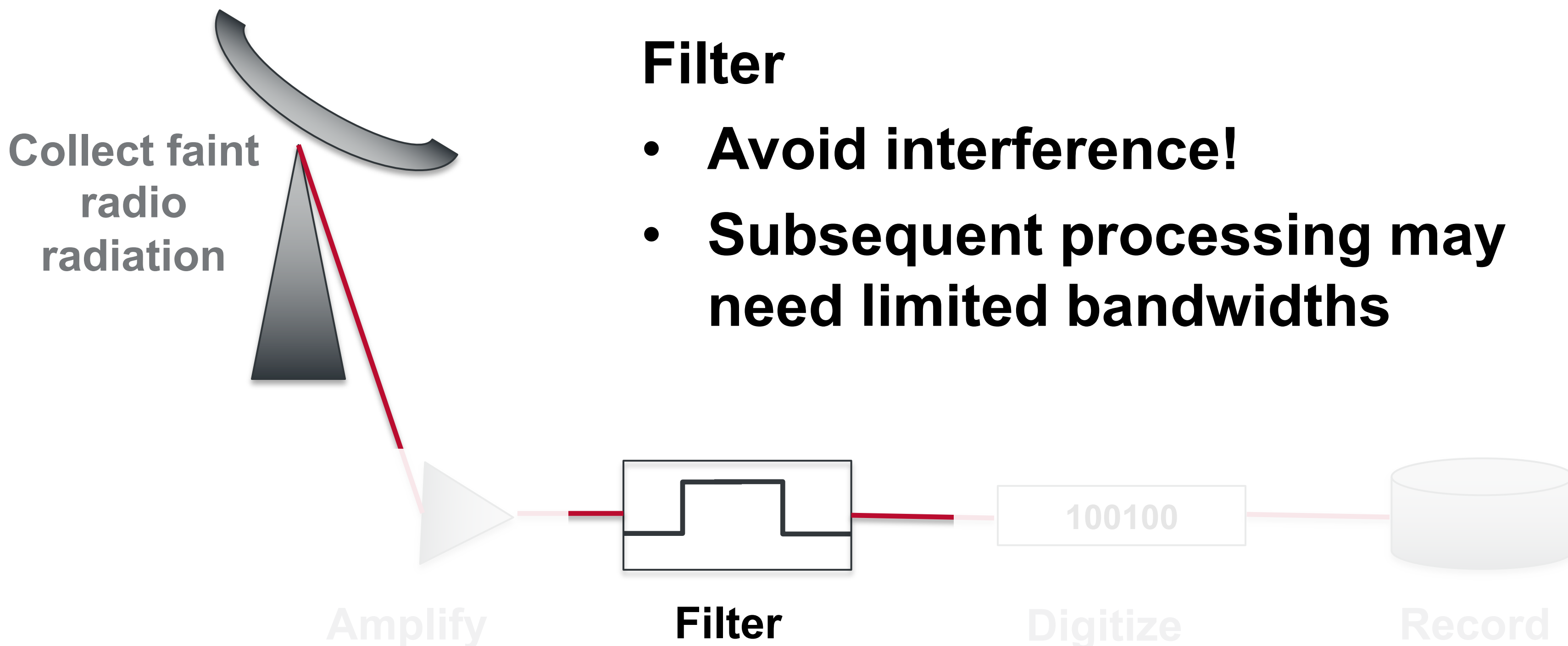


Radio Telescope

Amplification and Filtering



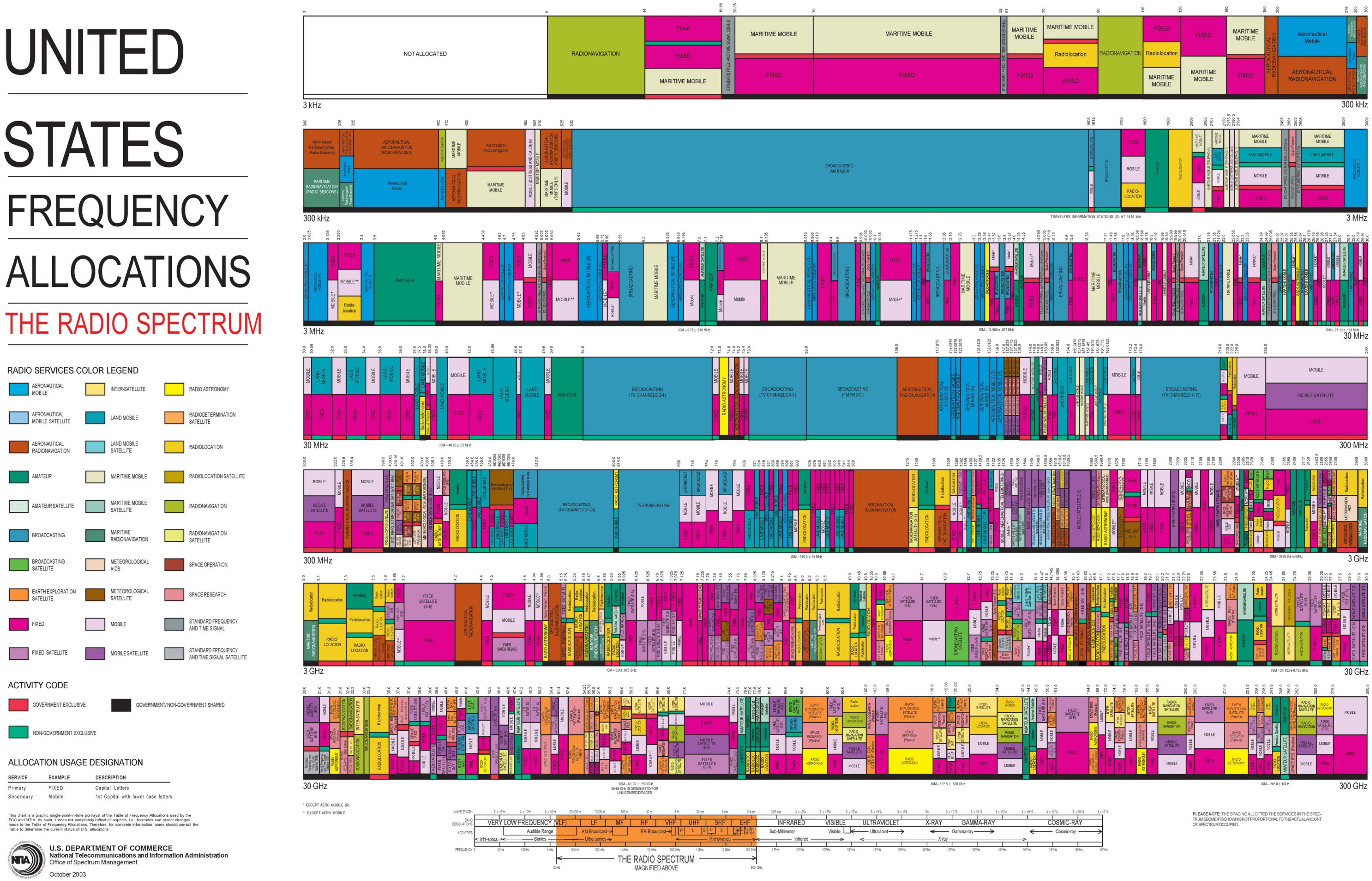
Conceptual Radio Telescope



Filter

- **Avoid interference!**
- **Subsequent processing may need limited bandwidths**

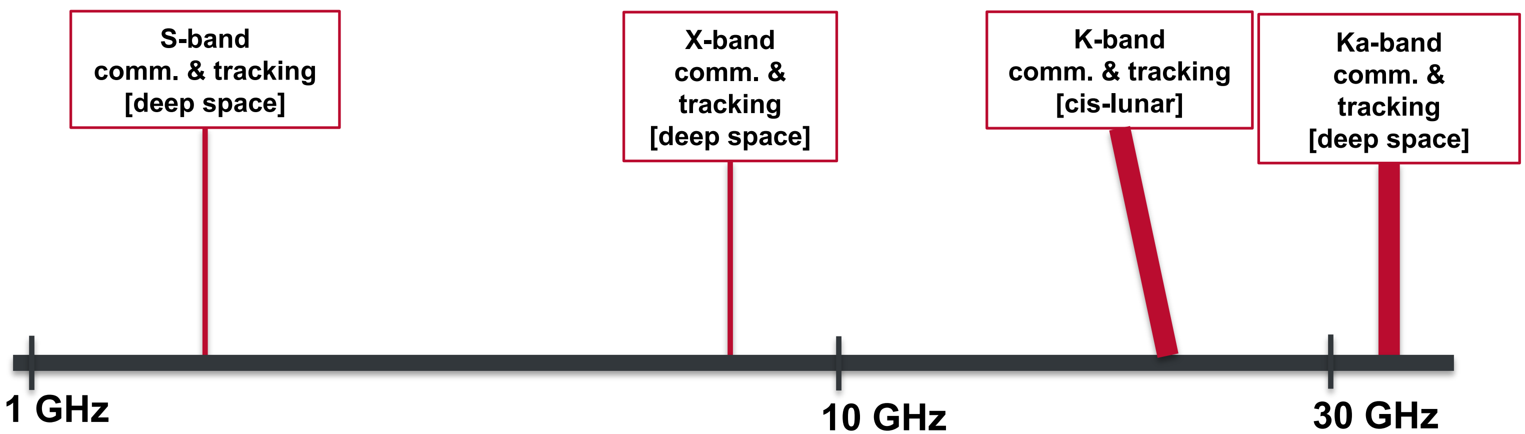
Interference!



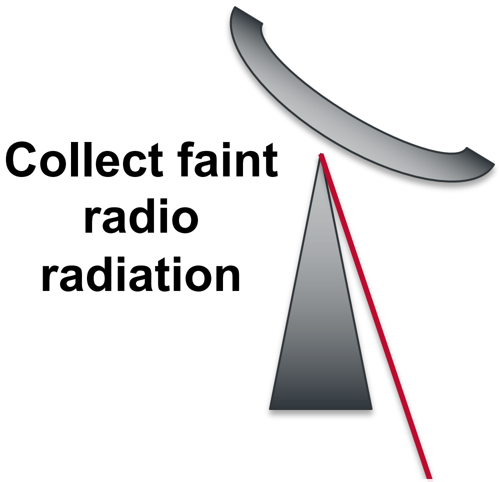
Spacecraft Communications

Required Frequency Coverage

Spectrum assignments agreed internationally

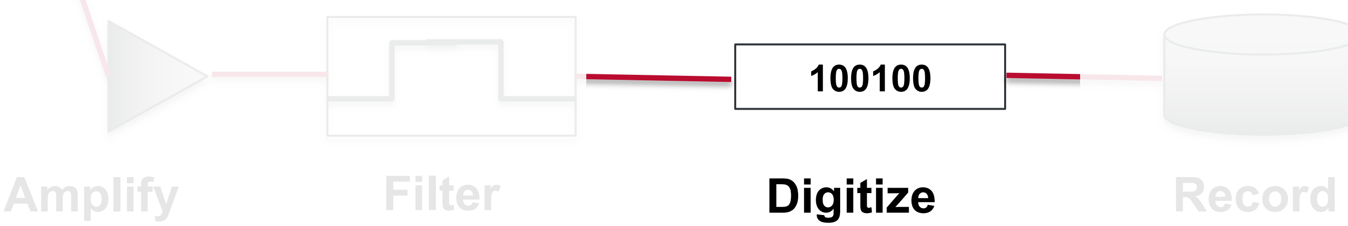


Conceptual Radio Telescope



Digitize

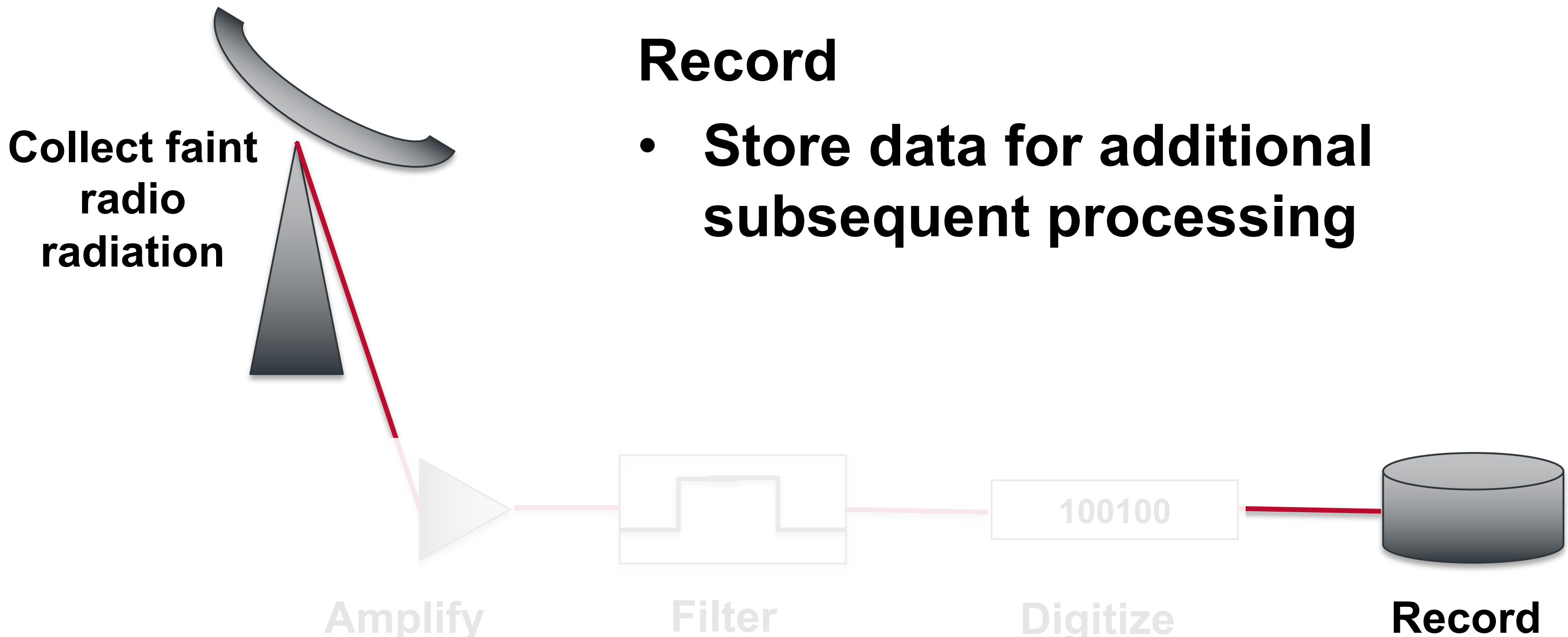
- Enables use of modern digital signal processing
- Better stability
- Enables error checking



Conceptual Radio Telescope

Record

- Store data for additional subsequent processing



Radio Astronomy

Large radio antennas, equipped with sensitive (cryogenic) microwave receivers

- **Spectroscopy**
  - **Complements ALMA, complements NASA and ESA far-infrared—sub-millimeter missions (e.g., Planck, *Herschel*, SOFIA)**
- **Very Long Baseline Interferometry (VLBI)**
  - **Complements VLBA, EVN, LBA; many NASA and ESA mission complements**
- **Time Domain**
  - **Many NASA and ESA mission complements**

Radio Astronomy Bibliography

Sardinia Deep Space Antenna Seminar Series

Joseph Lazio

Jet Propulsion Laboratory
California Institute of Technology

Bibliography

Eighth NAIC-NRAO School on Single-Dish Radio Astronomy, https://science.nrao.edu/science/meetings/2015/summer-schools/single-dish-program

Condon, J. J., & Ransom, S. M. 2016, *Essential Radio Astronomy* (Princeton Univ. Press: Princeton, NJ) ISBN: 9780691137797; https://www.cv.nrao.edu/%7Esransom/web/xxx.html

Wilson, T. L., Rohlfs, K., & Hüttemeister, S. 2013, *Tools of Radio Astronomy*, Astronomy & Astrophysics Library (Springer-Verlag: Berlin) ISBN 978-3-642-39949-7

Thompson, A. R., Moran, J. M., Swenson, G. W., Jr. 2017, *Interferometry and Synthesis in Radio Astronomy*, 3rd Edition (Springer Nature: Cham, Switerland) ISBN 978-3-319-44429-1; https://link.springer.com/book/10.1007/978-3-319-44431-4

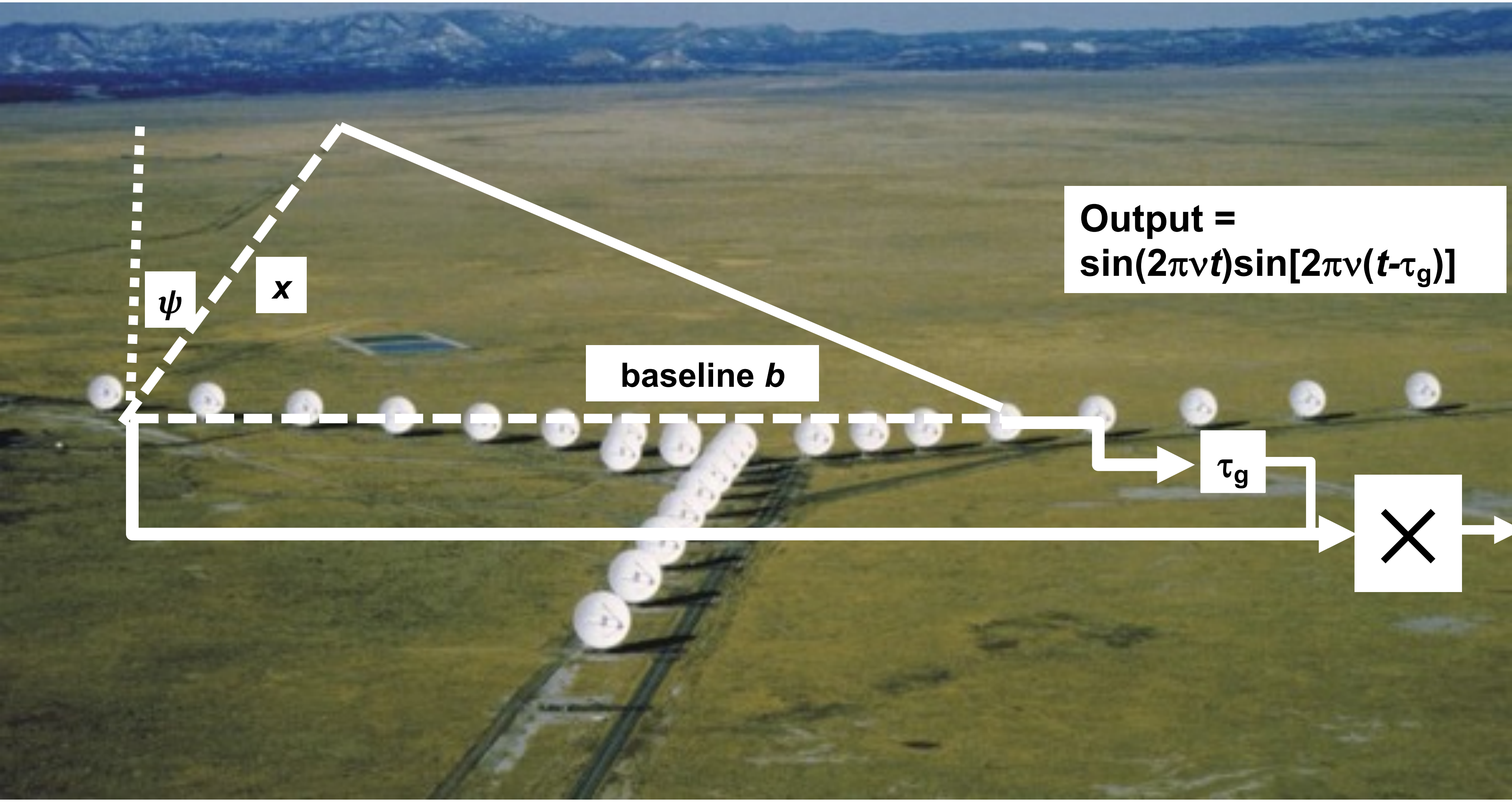
Kellermann, K. I., & Verschuur, G. L. 1988, *Galactic and Extragalactic Radio Astronomy*, 2nd Edition (Springer-Verlag: Berlin)

Valuable introduction, even if dated

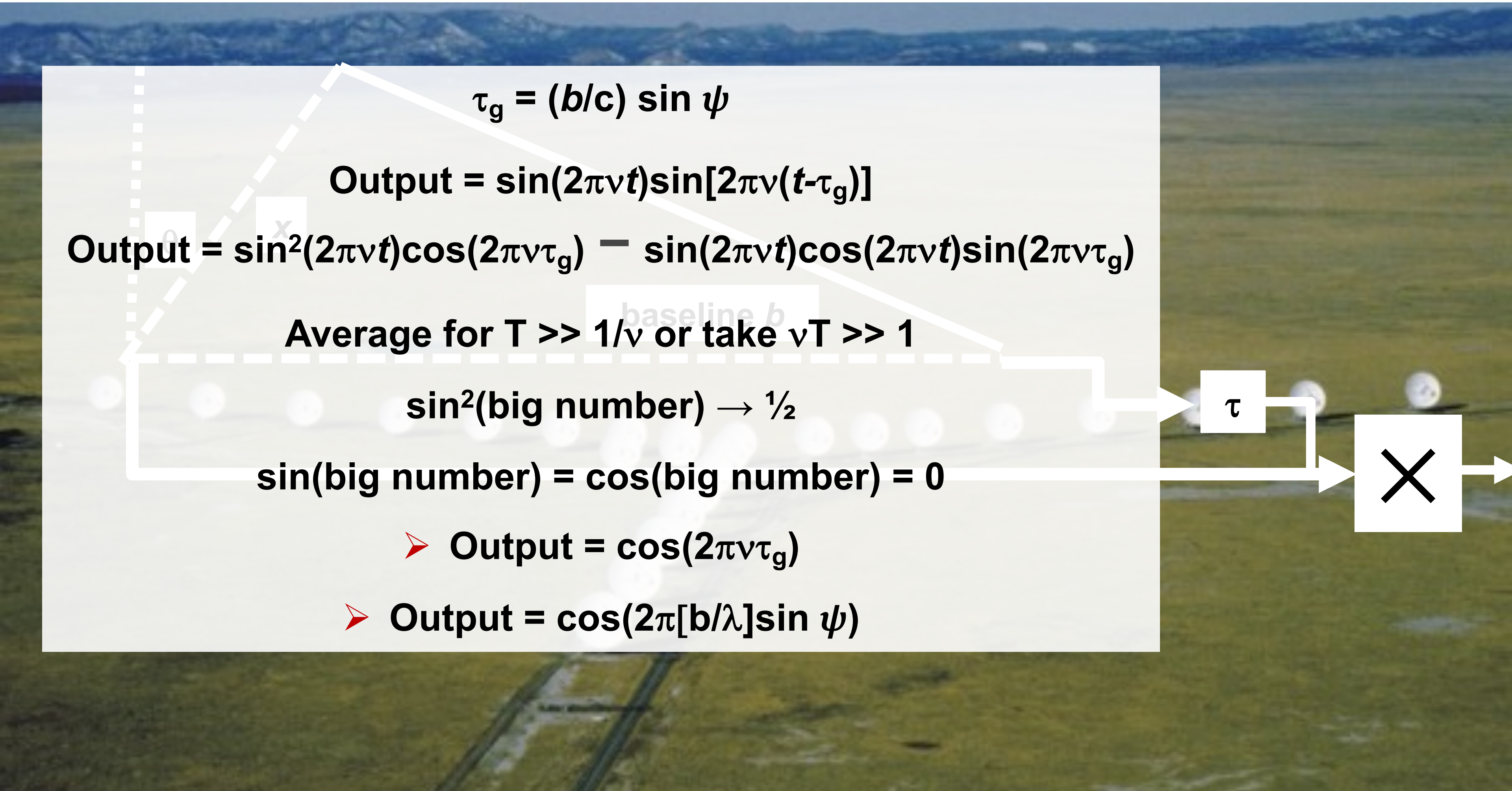
Science with a Next Generation Very Large Array, eds. E. Murphy & ngVLA Science Advisory Council (Astronomical Society of the Pacific: San Francisco) ISBN: 978-1-58381-919-7; http://aspbooks.org/a/volumes/table_of_contents/?book_id=592

Valuable introduction to radio astronomy, though focused on arrays

Aperture Synthesis Fundamentals



Aperture Synthesis Fundamentals



$$\tau_g = (b/c)\sin\psi$$

$$\text{Output} = \sin(2\pi\nu t)\sin[2\pi\nu(t-\tau_g)]$$

$$\text{Output} = \sin^2(2\pi\nu t)\cos(2\pi\nu\tau_g) - \sin(2\pi\nu t)\cos(2\pi\nu t)\sin(2\pi\nu\tau_g)$$

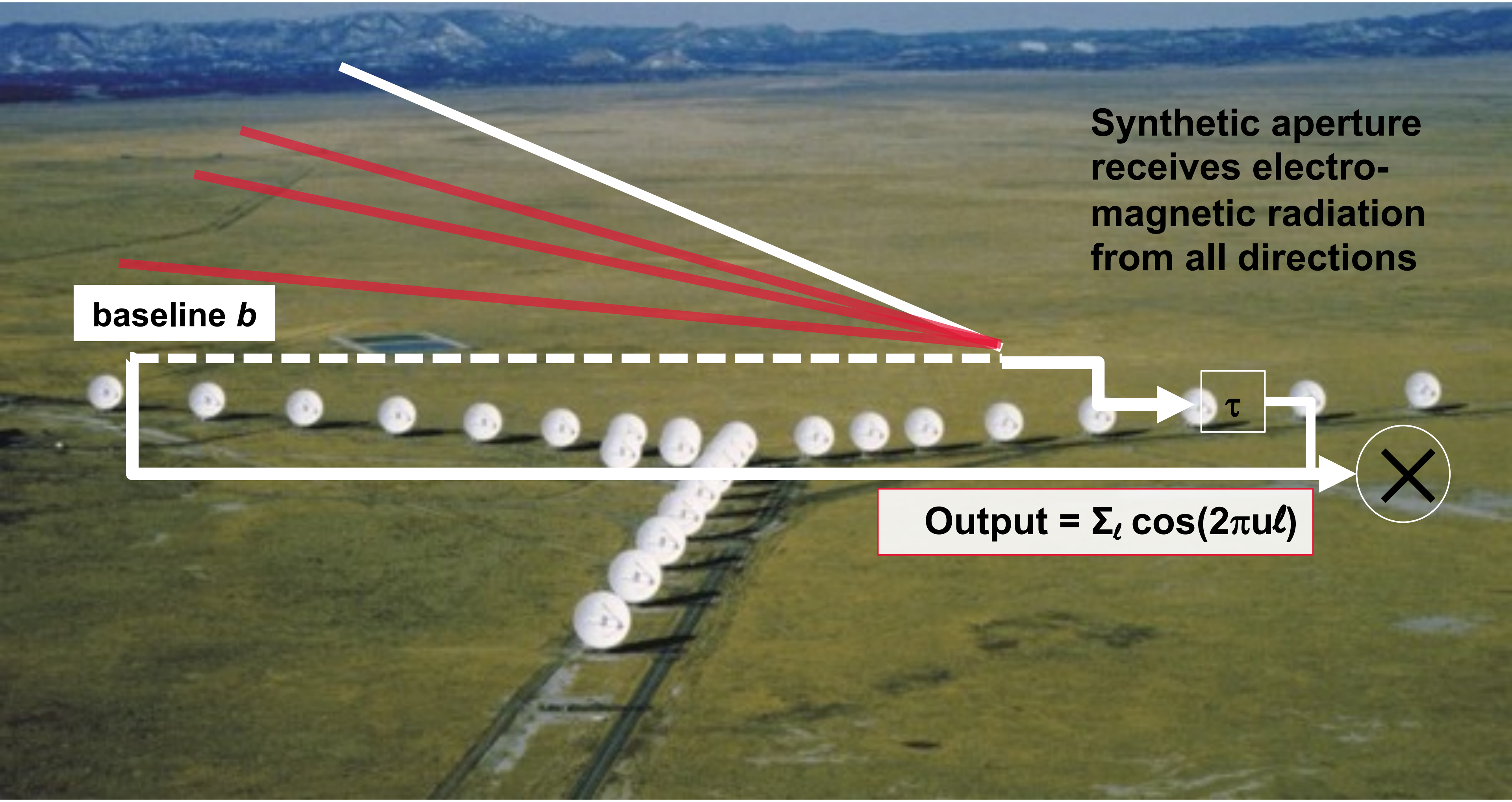
Average for $T \gg 1/\nu$ or take $\nu T \gg 1$

$$\sin^2(\text{big number}) \rightarrow \tfrac{1}{2}$$

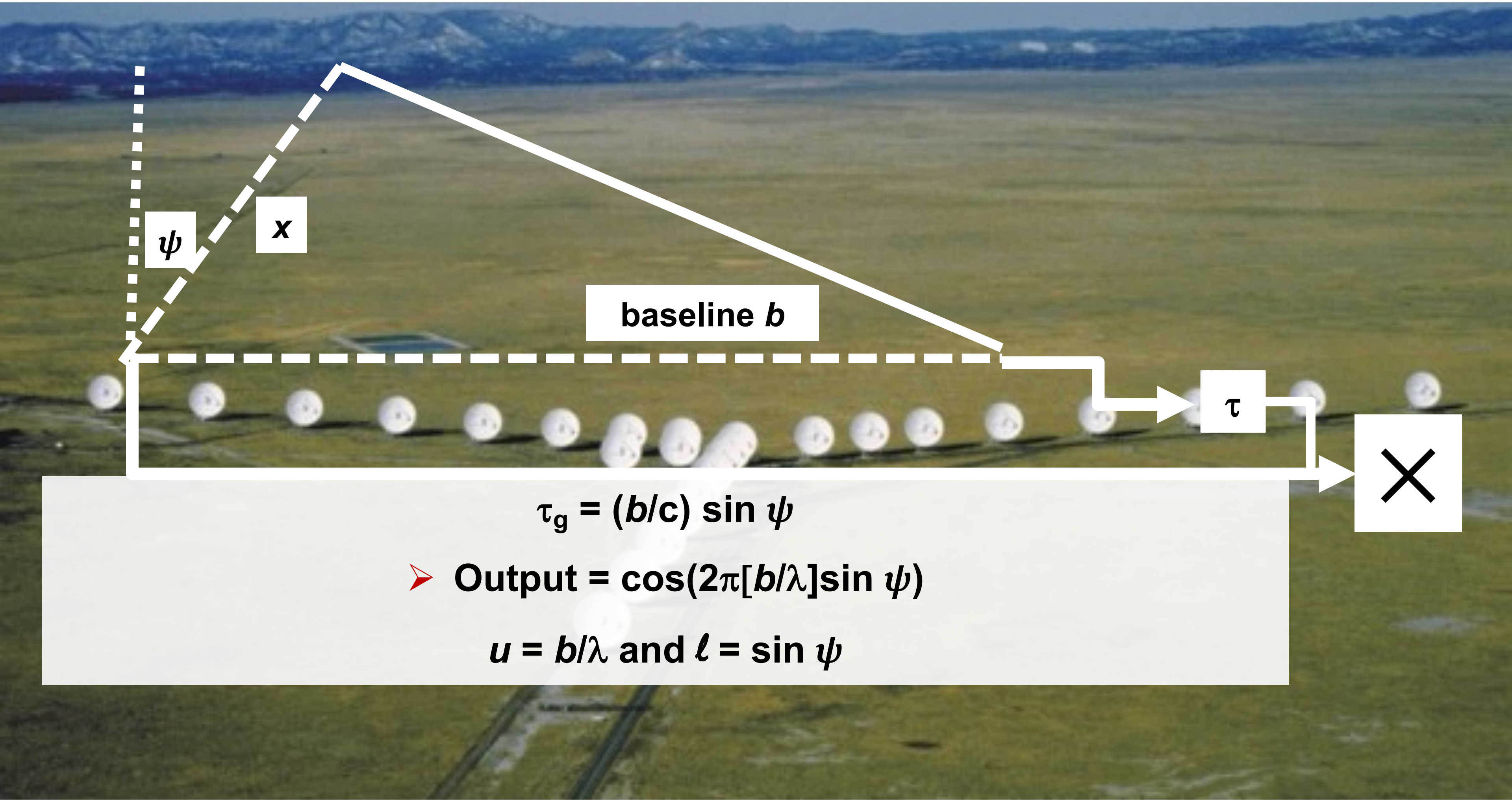
$$\sin(\text{big number}) = \cos(\text{big number}) = 0$$

- ➢ $\text{Output} = \cos(2\pi\nu\tau_g)$
- ➢ $\text{Output} = \cos(2\pi[b/\lambda]\sin\psi)$

Aperture Synthesis Fundamentals



Aperture Synthesis Fundamentals

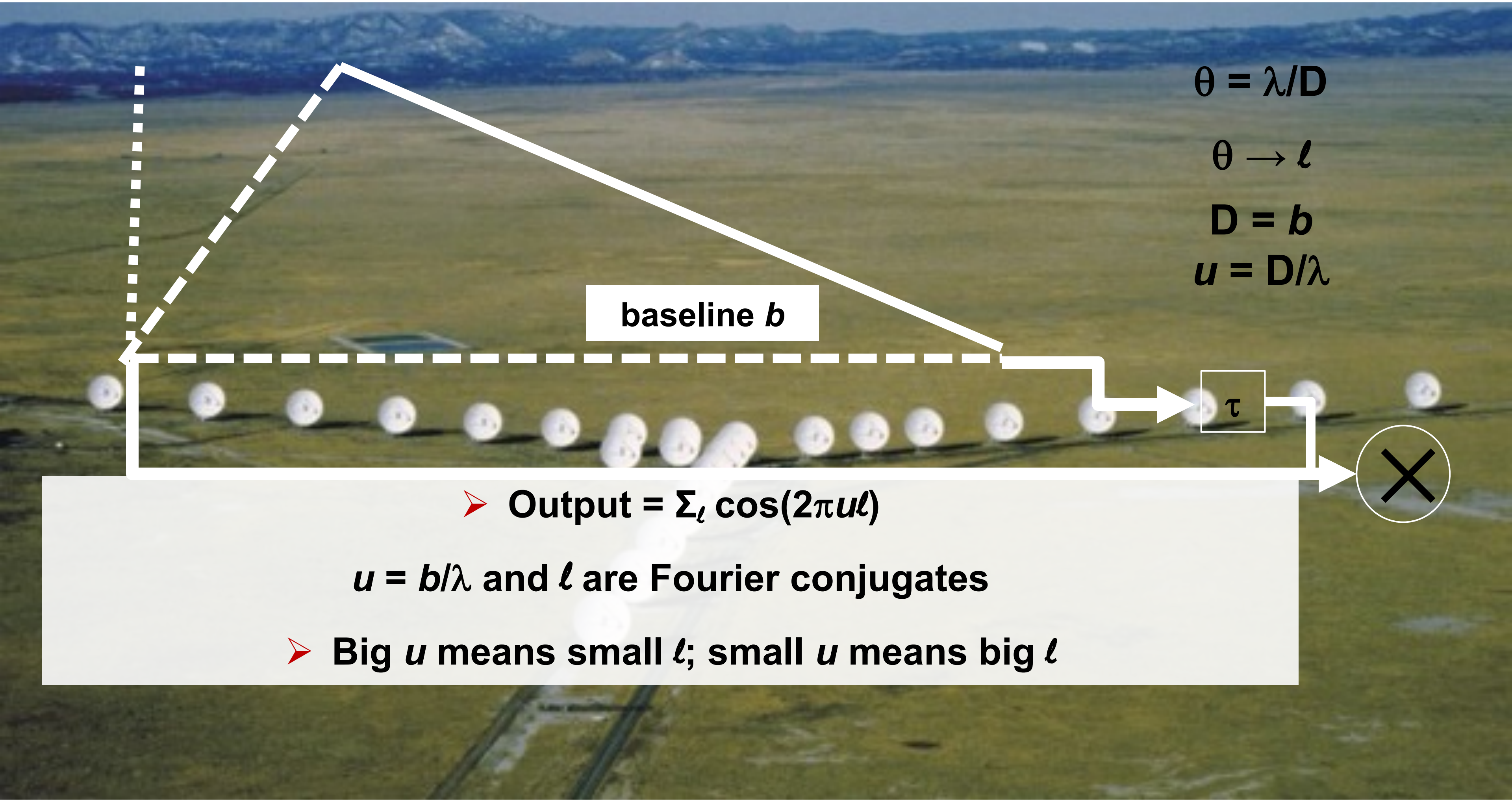


$$\tau_g = (b/c)\sin\psi$$

- ➢ **Output** $= \cos(2\pi[b/\lambda]\sin\psi)$

$$u = b/\lambda \text{ and } \ell = \sin\psi$$

Aperture Synthesis Fundamentals

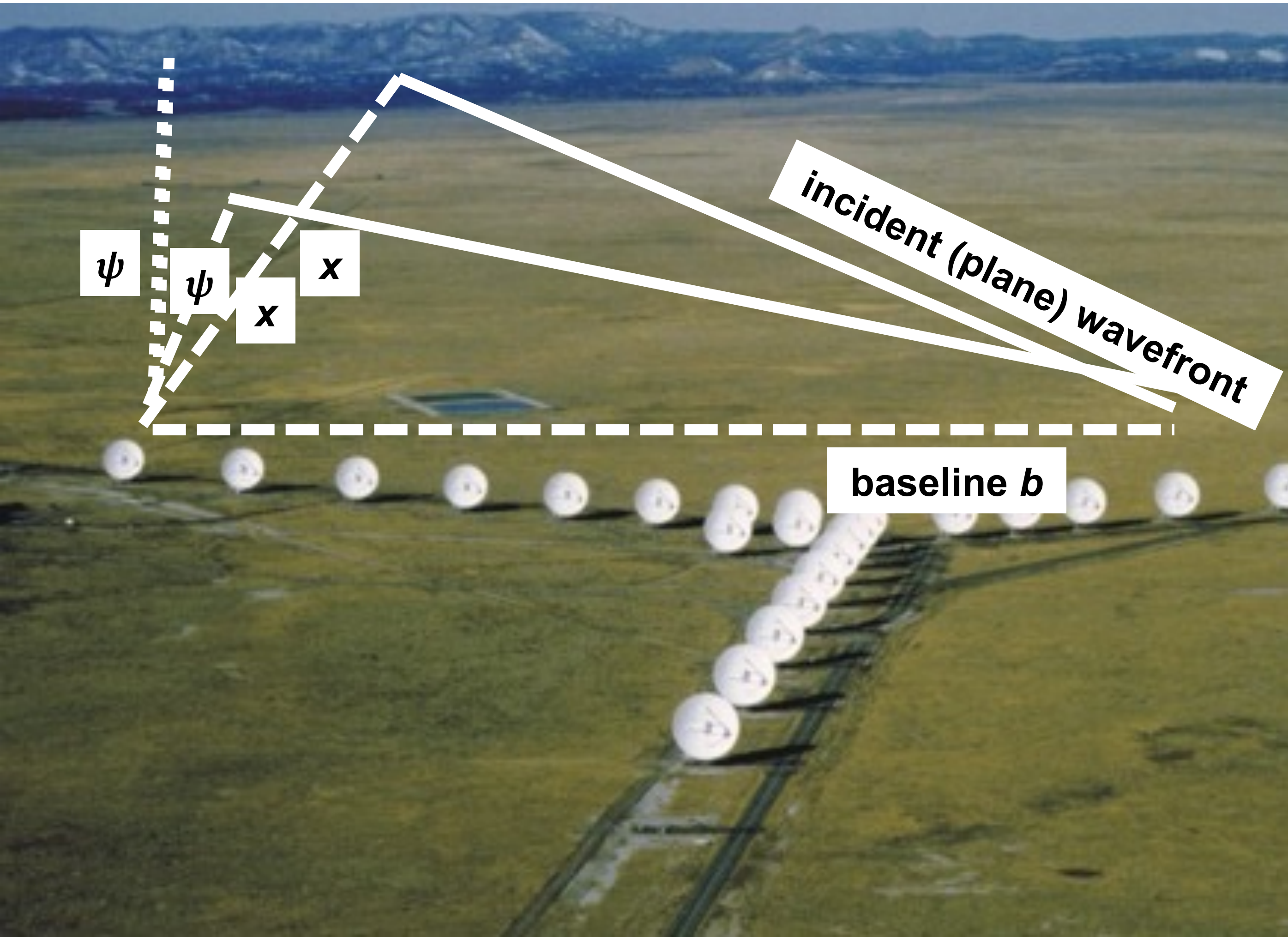


- Output = $\Sigma_\ell \cos(2\pi u\ell)$

$u = b/\lambda$ and ℓ are Fourier conjugates

- Big u means small ℓ; small u means big ℓ

Earth Rotation Synthesis



Geometric delay:
$\tau_g = x/c = (b/c) \sin \psi$

- **From perspective of distant observer, array changes shape**